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Ultrasound Techniques for Leak Detection

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ABSTRACT

Leak detection of vehicle cabin interiors is an important quality inspection phase that typically has been handled with various time consuming, or potentially product damaging techniques. Leak detection in tank or pressure vessel applications is almost always a concern for gas or fluid containment in vehicles and in many other industries. Numerous techniques exist for the detection of leaks in these and other types of structures. When testing is required in a production environment, often the speed of leak detection is very important if all samples must be tested. The use of several ultrasound based methods for leak detection in vehicle cabins and pressure vessel applications is presented here. Ultrasound waves are typically classified as having spectral content greater than 20 kHz. In the case of leak detection in a production environment, frequently the ultrasonic spectrum is largely free from background noise content that dominates the audible spectrum. The method for the response measurement of ultrasonic signals presented here is with the implementation of high frequency microphones. The excitation methods presented here are an active method utilizing an ultrasonic emitter, a passive method relying on the passing of air through leak locations, and a vibro-acoustic method utilizing a small electro-dynamic shaker. The methods presented here have been tested for the existence of leaks in some structures, but have not been tested in this paper for the existence flaws and defects that may potentially lead to leaks in some structures after prolonged use.

INTRODUCTION

The detection of gas or fluid leaks in many types of structures is an area of much history and diverse testing methods. The detection of leaks in a production environment usually requires a method that can quickly assess the existence and possibly the location of any leaks that may exist in the structure. The method of leak detection described in this paper is the use of ultrasonic testing in three specific modes of operation depending on the application. These methods will be described as active ultrasound, passive ultrasound, and ultrasonic vibro-acoustic testing.

The structures of interest for leak testing can be extensive. The structures can range from the entire interior cabins of vehicles or aircraft, to most fluid or gas holding or passage structures used in almost any industry. These fluid or gas structures can be formed from one material, possibly a welded metal tank. They can also be a combination of mating structures joined by gasket materials, like an engine-to-head interface. Leak detection can be for reasons of human comfort, gas or fluid loss cost reduction, or for containment of toxic, flammable, or radioactive gases or fluids.

The speed of detection for leaks will almost always be important for leak testing of any production item. The most attractive production line leak detection systems will meet the defined requirements for leak size detection and perform the inspection as fast as possible. 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.

Leak detection in structures can probably best begin with a discussion about the detection of flaws, defects, and cracks in structures that may not necessarily allow for a passage of gas or fluid. It is these flaws that can understandably propagate into minor or catastrophic leaks in some structures, so the methods to find flaws, cracks, etc., are areas that have been extensively researched. Some of the common inspection techniques for finding flaws and cracks are: visual (with and without magnification), eddy current, magnetic particle, penetrant, radiography, ultrasonic, frequency response function, stress-based acoustic emission, thermography, holography, and shearography. Many of these methods have valuable and unique applications for defect detection. When the crack or defect also can be classified as a leak, other methods such as water bubble inspection, pressure decay, mass flow, trace gas mass spectrometer systems, gas field effect transistor systems are commonly used. When a combination of testing criteria includes: (1) complete through-hole (leak) detection, (2) testing medium to large volume systems, (3) non-damaging or non-contaminating, (4) relatively quick test time in a production environment, (5) possibility for relatively simple data processing and interpretation, then ultrasound based testing can become an attractive option for some applications and some leak rate requirements.

The main reason for investigating the use of the ultrasonic spectrum compared with the audible spectrum for detecting leaks is because the ultrasonic spectrum is often void of any significant background noise contamination. In some cases any ultrasonic background noise contamination can be reduced or eliminated with a designed isolation test chamber.

ACTIVE ULTRASOUND TESTING METHOD

The ultrasound testing method in the previous list of common leak test methods usually refers to the use of one or more emitters and receivers in various contacting or non-contacting configurations. These are typically referred to as pulse-echo and pulse-receiver techniques. All of these techniques can be described as an 'active' ultrasound method since the ultrasound is generated with an emitter. With these methods, an ultrasonic pulse is delivered into the structure and then the signal is either inspected with the same transmitter used as a receiver, or the signal is received with another transducer. Inspection of the echo-characteristics of the signal hitting internal components, material variations, flaws, cracks, etc., of a structure are often just performed in the time domain, but can also be inspected in the frequency domain. The very familiar advanced use of these techniques is for medical fetal imaging. These techniques have an attractiveness in many areas, but typically they do not have the advantage of quick implementation and quick testing for large and/or complex structures such as vehicles which are both materially and geometrically diverse.

ACTIVE ULTRSOUND TESTING IN VEHICLE CABINS

The active ultrasound leak testing of vehicle interior cabins in a production environment has been described by the authors previously[1]. The frequency range used for these methods described in this paper's tests has currently only been up to 100 kHz due to the ease of obtaining commercially available transducers available for noise testing. This defines the ultrasonic range to be approximately 20 – 100 kHz. Wavelengths will be in the 17 – 3.5 mm range for the described frequency range. This 20 – 100 kHz frequency range can be described as a Low Frequency Ultrasound range, since some applications utilizing ultrasound can reach well into the MHz range. As mentioned, an attractiveness for using the ultrasonic range is the potential for minimal background noise corruption in a production environment. The background noise environment may either have some narrowband or broadband regions of intermittent or continuous response, but it may also have regions where there is no significant background noise response. The ultrasonic leak testing for the vehicle application has been successfully achieved by using at least one transmitter placed inside of a closed vehicle. A frequency selectable narrowband signal is given to the transmitter and then commercially available high frequency microphones[6] are used to scan the window seals and doors for any acoustic emission of the transmitted signal passing through any leaks. Leaks in the range of 1 mm (1000 µm) or larger are typically of interest in this application and a 10-15 dB transmitted signal increase when a leak is encountered is easily found with this active method of ultrasound testing.

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[7] used as an emitter 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 utilizing this active ultrasound process. The data shown in Figure 1 is for a very slow scan of the window seal. Actual production implementation of this system has been handled by programmed robots carrying the microphones. This automated approach much more quickly scan the vehicle's entire known seal geometry.

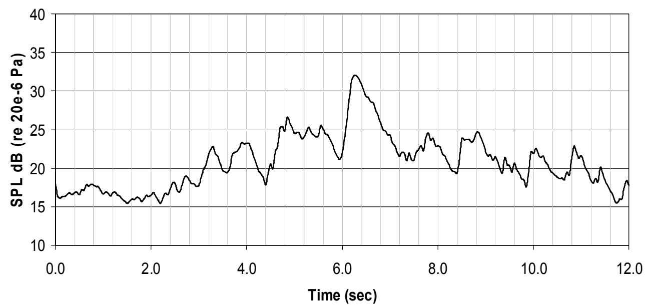

Figure 1. Low Frequency Ultrasound SPL response (2 kHz bandwidth slice) for leak detection in a production vehicle

Detection of intrusions and/or build variation in a fully trimmed vehicle cabin is an integral part of Quality Control for all automobile manufacturers. They have traditionally relied on test processes utilizing water, which is potentially damaging, costly, and raises environmental and plant safety issues. Traditional subjective noise evaluation is not only time consuming, but relies on favorable ambient conditions to conduct the testing, and can only be performed on a select few units.

Vehicle cabin leaks allow for the possibility of a number of annoying issues for the passengers that include wind noise, water leaks or road noise when the vehicle is traveling at a specific speed or a range of speeds. The causes of such water and wind noise issues can be as varied as; open seams, missing or damaged sealer, or misaligned, damaged or missing components. Detecting and locating such problems has been a challenge for automobile manufactures for decades. Given the wide variety of sources of this problem, the use of ultrasound allows for a unique testing solution with many advantages.

This ultrasonic system described here for leak detection identifies and locates intrusion points and/or build variation in a non-destructive fashion while operating within normal production line conditions. This technology provides an accurate, repeatable, automated, and unbiased data instrument empowering the manufacturer to adopt a quantitative scale of measurement.

ACTIVE ULTRASOUND TESTING IN TANKS

The active ultrasound method was also previously described by the authors for the application of pressure vessel leak detection[1]. That paper showed success in detecting leaks in water tanks with leak sizes of approximately 350 μm utilizing the Low Frequency Ultrasound range. That leak size is considered to be a significant leak that can often easily be detected, externally with visual means. Tanks with known leaks an order of magnitude smaller than 350 μm were not detected successfully using the active Low Frequency Ultrasound range. Several plugs were then made to have leaks ranging from 3 – 40 μm for the purpose of determining if active ultrasound up to 100 kHz could detect leaks in that size range. These plugs were made with a laser forming process and then the holes were inspected under a microscope to determine the external dimensions. The tests showed no acoustic emission for even the 40 μm plug in the Low Frequency Ultrasound range using this active method.

These above listed ultrasound methods are described as active methods since a known signal is generated and delivered to a transmitter. The passive method of ultrasound testing involves the detection of the turbulent response due to passing air through a hole and/or the turbulent response encountered by a microphone passing through a stream of airflow.

PASSIVE ULTRASOUND LEAK TESTING OVERVIEW

The method of ultrasound leak testing described here involves introducing a pressure or vacuum on one side of a tank or pressure vessel. The gas most easily used is just air. The other gases often used are for various types of pressure based testing are helium and or nitrogen and hydrogen. These gases are used due to the smaller atomic size of the molecules compared with air. This typically allows smaller sized holes to be detected. A high frequency commercially available microphone with a frequency response up to 100 kHz is again used for the method described here to detect the presence of air passing through any vessel leak locations. The passing of air through small leaks can create turbulent flow which is detectable in the ultrasound frequency range. Again, this frequency range can be very attractive due to the lack of other background noise sources in this range. Additionally, if the microphone passes directly in line with the airflow, then the airflow will cause ultrasonic response due to the turbulence generated when the air hits the microphone's grated covering. The fact that there is ultrasound response as a result of air flow, and not generated by a transmitter, is the reason for the 'passive' ultrasound label for this type of testing.

Though a vacuum test environment has not been inspected for the applications presented in this paper, Holland[2,3], et al, have described detecting the local ultrasonic structural vibration in the vicinity of a leak caused by the gas passing through the leak in a spacecraft environment. The fact that the outside environment to the spacecraft exists as a vacuum means that a turbulent flow of air isn't detected on the inside of the aircraft, led to their approach to inspect for the structural vibrations near the leak. Holes as small as 1 mm were shown to be found with this method.

Passive-type ultrasonic testing has existed for quite a while. It is commonly used to find air or gas leaks in plant environments. Typically a handheld ultrasonic receiver is used to scan pipe joints to find any small levels of ultrasonic response due to gas leaks. The ultrasonic signal can then be heterodyned into a lower, audible frequency range where an operator with headphones can listen to this altered signal to make an assessment about a leak's existence and location. The process works well for the intended industry but does require close scanning of seams and joints to allow for detection. The human operator method would not be a solution, for example, for quick testing of many pressure vessel samples in a production environment due to the operator's lack of speed to repeatedly scan possibly 3 to 15 feet of welded seam length of a pressurized vessel.

PASSIVE ULTRASOUND LEAK TESTING SAMPLE RESULTS

Tanks from one manufacturer that have been labeled as rejected samples due to leaks detected with their current water bubble method have given excellent leak detection results with this passive ultrasound method described. Tank pressures in the 70-80 psig range allowed for easy leak detection for this particular manufacturer. Figure 2 shows the ultrasonic sound pressure level response when a known leak was emitting air in a 90 degrees direction with respect to a microphone placed on each side of the tank. The background noise level is also shown for comparison. Any other orientation of the tank/leak with respect to the microphones had shown greater SPL response in the ultrasound region. This figure shows the lowest response detected due to the orientation, but it is still very easily discernable that there is a leak.

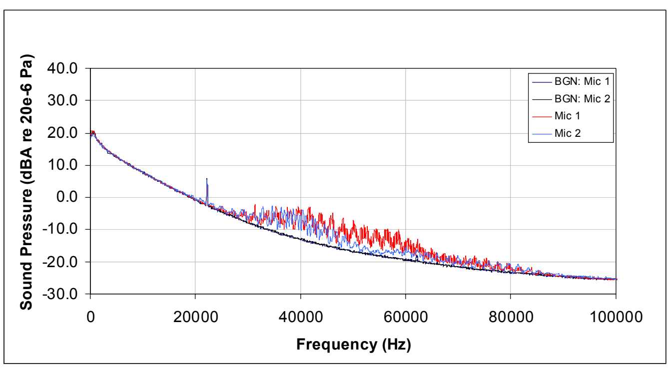

Figure 2. Low Frequency Ultrasound SPL response for a tank pressurized to 70-80 psig

The concept of a tailored sound chamber environment that can surround a pressure vessel during passive ultrasound testing is attractive for two main reasons: (1) it can provide isolation of possible ultrasound background noise corruption, and (2) it can provide a reflective, diffuse environment for the leak's ultrasonic response to be 'captured' more easily with even just a single microphone. Figure 3 shows the results of a tank with the previously described designed 20 µm plug installed and surrounded by a small, enclosed, reflective chamber. The leak source distance to the microphones is the same as the test for Figure 2. The leak's location with respect to the microphones was positioned everywhere while in the chamber and the SPL results were the almost the same magnitude as the results in Figure 3, irrespective of the leak's location.

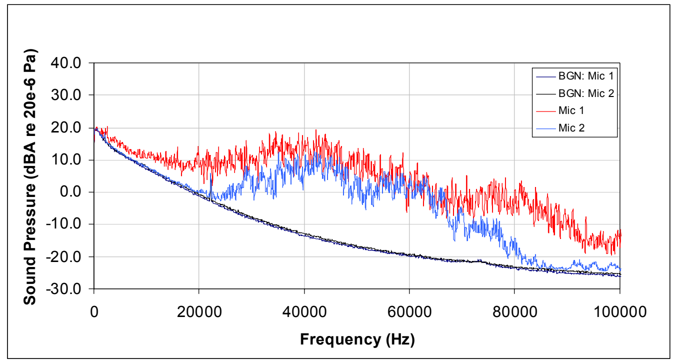

Figure 3. Low Frequency Ultrasound SPL response for a tank pressurized to 70-80 psig with a known 20 µm leak and enclosed in a small sound chamber.

It can be proposed that smaller chamber volumes can be designed to encompass just the external welded seams of very large tanks, such that only a small volume of high pressure air needs to be used. A microphone could be placed inside of the non-pressurized tank to detect ultrasonic response due to air passing from the outside to the inside of the tank. This method is currently being investigated.

It is intuitive that with increasing tank pressure, the flow rate can increase through a leak up to a certain point, and the detection capability can increase for holes currently known to be as small as 20 µm based on the testing described here. It is for this reason that holding tanks that are not designed to handle pressure greater than 1-2 psig, ultrasonic testing may show difficulty in detecting the smaller leaks with this method.

This passive ultrasonic method for these applications has the advantage of almost instantly being able to detect ultrasonic response after sufficient pressurization has been achieved. Common pressure decay based methods used for leak testing need to wait for any pressure loss vs. time to have taken place before a pass/fail assessment can be made regarding a leak's existence.

VIBRO-ACOUSTIC LEAK DETECTION METHOD

A vibro-acoustic method capable of leak detection in certain pressure vessel applications is presented here. The test structures were pressure vessels that have thin membranes internally covering unused pipe plug holes. These membranes can have faulty assembly problems in some cases and can potentially not seal as desired. An attractiveness of this method is that it does not require pressurizing the vessel. This can be more important as the pressure vessel size becomes large. The test method involves using a small electro-dynamic shaker[8] with a swept sine excitation between 20 Hz – 8 kHz. The idea is to excite any resonant conditions that exist between any fractured membrane material that is bounded by the plug hole in the tank structure. The response of any resonance is again monitored with a high frequency microphone to make use of the Low Frequency Ultrasound range. The shaker is attached to the tank with a nylon stinger. This attachment method along with the selected excitation range eliminated any non-linearities that could give any false leak detection results. The ultrasonic response near the shaker was simultaneously monitored to eliminate any suspicions about other sources of the ultrasonic response detected near a potential leak location.

Figure 4 shows the peak sound pressure results for the excitation of a pressure vessel with two fractured, faulty membranes at two different locations compared with eight membranes that were not faulty. The microphone was placed within 5 mm of the surface of each of the holes and the peak SPL response was measured during the vibration excitation. The high peak response in the ultrasonic range is an indication of a faulty membrane. To confirm the existence or absence of leaks, these tanks were pressurized with air and the leaks were evident with both passive ultrasonic inspection and water bubble inspection.

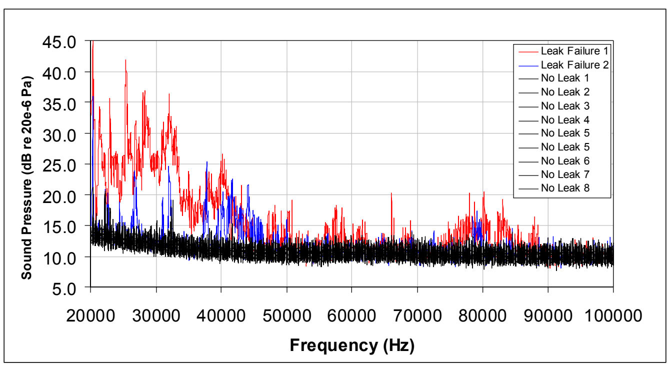

Figure 4. Low Frequency Ultrasound SPL peak response for tanks with two faulty membranes and tanks with no known leaks.

Vibro-acoustic techniques have been heavily utilized for many types of defect detection for the full spectrum range. They can be in the form of a frequency response function format, or standard response-only frequency presentation. Some type of a contacting response transducer is more often utilized than a non-contacting method to get a better signal to noise ratio due to the attenuation of ultrasound in air. The non-contacting microphone response transducer displayed here has shown to be suitable for this particular application and can allow for more quickly scanning the plug holes.

The pressure vessels tested here are certainly not homogeneous structures, in that they have various thicknesses in the shell wall compared with the welds and compared with the attached plumbing hardware. Though, it turns out that these mentioned variable structural and material characteristics are largely similarly homogenous compared with the very thin walled membrane material portions of these particular tanks. It is this structural difference for this application that allows for success with this method. If the structure had contained easily excited components attached to its structure not related to leak containment, then this basic ultrasound method may not be suitable.

With these particular membrane structures, it was rather easy to detect the through-hole defects with this basic vibro-acoustic method. More difficult to detect cracks, flaws, and corrosion have been shown to be detectable in some applications with a more involved method often referred to as a non-linear vibro-acoustic modulation technique[(4,5)]. The technique typically involves making use of the non-linear vibration characteristics of weak structures. If a lower frequency global vibration is input to a structure, and a high frequency signal also input into the structure, then this signal can be modulated by the non-linear vibrations of certain types of defects. Often, sidebands are then evident around the high frequency carrier signal. At the time of this writing, this technique is being investigated for feasibility of leak detection in some unique applications, along with the important realizable speed of detection for these applications.

CONCLUSION

The use of ultrasound for non-destructive testing is a broad field that has many uses. Some applications for the use of ultrasound testing have been described here. The successful detection of vehicle window and door seal leaks sized at ~ 1 mm that contribute to wind noise, water leaks and road noise issues has been described using an active ultrasound method in a production environment with automated test systems that currently exist. Additionally, the testing for leaks sized at ~ 20 µm in tanks or pressure vessels has been described by using a passive ultrasound method with pressurized air. Lastly, a vibro-acoustic method that does not require the vessel to be pressurized has been described for leak detection in a special pressure vessel application.

The ultrasound method used for the vehicle cabin leak detection allows for easy leak source localization. This is because the system described uses scanning robots holding the microphones to pass all possible leak locations. The pressure vessel applications were investigated in this paper with a leak detection approach rather than a leak location approach. The highly directional nature of ultrasound can allow for leak source localization in the pressure vessel applications with a feasibility study.

The ultrasound methods described here have only been described for a few select applications. These methods may not be suitable for all applications due to very small leak sizes required for inspection. The pressure based passive methods may not be suitable for structures that are not designed to allow for much pressurization, and structures that have gaskets in their design. Therefore, a feasibility study is recommended prior to applying Low Frequency Ultrasound techniques to products significantly different from those described in this paper.

ACKNOWLEDGMENTS

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