10/1-16-96 JSC

SANDIA REPORT

SAND96-8202 • UC-74

Unlimited Release

Printed December 1995

Feasibility Study Using Non-Contact Ultrasonic Sensors for Assessing Reservoir Fill State

Shermann Min, Wei-yang Lu

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94551
for the United States Department of Energy
under Contract DE-AC04-94AL85000

Approved for public release; distribution is unlimited.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of the contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

This report has been reproduced from the best available copy.

Available to DOE and DOE contractors from:

Office of Scientific and Technical Information
P. O. Box 62
Oak Ridge, TN 37831

Prices available from (615) 576-8401, FTS 626-8401

Available to the public from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.
Springfield, VA 22161

FEASIBILITY STUDY USING NON-CONTACT ULTRASONIC SENSORS FOR ASSESSING RESERVOIR FILL STATE

Shermann Min
Exploratory Systems Department

Wei-yang Lu
Experimental Mechanics Department

7011 East Avenue
Sandia National Laboratories
Livermore, CA 94551-0969 USA

ABSTRACT

The change out of reservoirs in weapon systems can pose a significant safety threat if the reservoir has inadvertently transferred its contents. While the possibility of this occurring is very remote, the consequence can be extremely severe. There is therefore a need for equipment and procedures to determine the gas containment status before the component is removed from the weapon during normal maintenance procedures. The objective of this project was to demonstrate the feasibility of using ultrasonics to detect a change in stress states of a filled and unfilled reservoir. Electromagnetic-acoustic transducers (EMATs) and laser ultrasonics (LU), two non-contact ultrasonic techniques, were examined. A second approach which measures the changes in modal resonances was also explored. This report summarizes the experimental results from an initial feasibility study aimed at demonstrating the use of acoustics to determine the gas containment status of GTS reservoirs.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED .

go

FEASIBILITY STUDY USING NON-CONTACT ULTRASONIC SENSORS FOR ASSESSING RESERVOIR FILL STATE

I. INTRODUCTION

The gas containment status of a pressure vessel is readily obtained via a measurement of the additional total mass, if the mass of the vessel itself is known. In most cases, however, this measurement is not possible because the unit is already installed as part of the system, or the mass of the reservoir is not known precisely. Another method to deduce the amount of trapped gas is to measure the internal pressure. Although pressure sensors with large dynamic ranges are widely available, the requirement of internal access deems this approach undesirable, if not unfeasible. We are thus limited to external means which infer gas containment status through other physical phenomena.

Several techniques which attempt to accomplish this task are currently in use, each of which is limited in some fashion regarding its application. Thermal measurements, for example, rely upon the heat generated from the radioactive decay of the contained gas and is therefore applicable only to certain radioactive gasses (i.e. tritium). A resistance measurement of the bridge wire in the valve actuator circuit infers containment status by determining whether the valve has been fired. Although the measurement itself has been determined to be of minimal risk, the procedure requires some additional disassembly and the making of an electrical connection with the valve firing circuit itself. While the probability is remote, a leaky pinch weld will not be detected by a resistance measurement since the bridge wire is not affected in such an event.

Transferring or venting of the contained gas also causes a fundamental change in the state of the material, namely a reduced level of stress and hence strain. Sensors based on measuring this change in strain must be able to assess differences in wall strain of 500 to 2000 microstrain (filled) and 0 to 100 microstrain (empty) on reservoirs that have been in the weapon system for several years. Conventional and optical fiber-based gauges can measure strains on these scales but cannot sustain accuracy over the required time periods due to calibration errors caused by aging (i.e. degradation of the reference upon which these gauges are based). Given the proper technique and conditions, ultrasonics provides a method for determining material stress and strain that is not susceptible to degradation problems caused by sensor aging, since the measurement is based on the material properties of the reservoir wall.

The measurement of strain using ultrasonics is straightforward since, by definition, the material geometry and hence the wave propagation path length has changed. Current state-of-the-art ultrasonic gauges have a resolution on the order of 0.001" for most metals. An ultrasonic approach for measuring stress depends upon the acoustoelastic effect, which refers to the fact that elastic wave velocities vary linearly with stress, provided that the stress is below yield [1]. Conceptually, this relation may be described by the equation: $v = v_0 + k\sigma$, where v_0 is the stress-free wave velocity, σ is the material stress, and k is the acoustoelastic constant. Accurate measurements of the stress-induced velocity changes yield information which can lead to the determination of stresses in the body. Advances in electronics, sensor technologies, and modern signal processing now make it possible to extract stress-related features from an ultrasonic signal using prior knowledge of a specimen's material properties and its environment. Furthermore, ultrasound may be generated and detected without any physical contact with the specimen under interrogation through the use of electromagnetic-acoustic transducers (EMATs) and/or lasers (LU). A description of these two ultrasonic methods is given in the next section.

A second approach examined as part of this feasibility study is the measurement of modal resonances when a filled and unfilled reservoir is given an impulsive excitation. Just as an instrument string vibrates differently when tightened, natural vibration frequencies of an object vary with both applied and residual stresses. The Frequency Response Method (FRM) is based upon the measurement of acoustic or wall vibrations after broad band energy has been imparted to the object. When white noise or an impulse is imposed upon a mechanical structure, the geometry, material, and other properties of the body determine which vibration frequencies can exist. The power spectrum of such a response thus becomes a unique signature which can only be repeated under identical conditions. The peaks of this plot, or the modal resonances as they are often called, are affected by the material stress as well as the boundary conditions. With all else being equal, filled and unfilled reservoirs respond differently due to wall stress and the mass contained within the pressure vessel. An analysis in the frequency domain of either the overall acoustic response or the wall motion of the reservoir yields the desired information.

II. BACKGROUND

Two advanced non-contact techniques for generating and detecting ultrasound were examined as part of this feasibility study, each with different emphases. Both techniques were aimed at measuring the acoustoelastic effect in order to infer wall stress and hence the

gas containment status. An approach involving the examination of modal resonances as an indicator of fill state was also investigated. The following is a brief summary of each method and their relative benefits and drawbacks.

Electromagnetic Acoustic Transducers (EMATs)

EMATs excite and detect the ultrasonic waves through direct electromagnetic interaction [2]. A serpentine wire, or wire coil, carrying an oscillating current, is placed in proximity to the surface of an electrically conducting specimen, thus generating an image eddy current of skin depth. An external magnetic field, supplied by either permanent or electromagnets within the transducer assembly, causes a Lorentz force in the material to initiate the propagation of stress waves. Ultrasound detection is accomplished via the same mechanisms in the reverse order. Figure 1 is an illustration of a typical Lamb wave EMAT. Unlike conventional piezoelectric transducers, EMATs are wavelength devices; that is, the wavelength is fixed by the wire or coil spacing. The wave velocity within the host medium then determines the actual frequency of the ultrasonic wave. While EMAT transmitters are typically narrow band devices, EMAT receivers may be either narrow band or broad band, depending upon their design. Reducing the bandwidth of the receiver clearly increases sensitivity while broad band receivers increase signal fidelity and may be used with a variety of generation mechanisms (e.g. a laser source).

As mentioned above, EMATs are non-contact devices which operate through electromagnetic forces. Thus, they do not require the use of an energy couplant, nor do

Figure 1: Illustration of a typical Lamb wave EMAT. The transmitter consists of a wire coil and a magnet. An AC current is pulsed in the wire coil, generating an image eddy current in the sample. Due to the Lorentz force, stress waves are created.

they generate waste or disturb the specimen under inspection in any fundamental manner. Depending upon the configuration of the wire coil and internal magnets, specific wave types and modes may be preferentially excited, often with greater ease than conventional means such as piezoelectrics. Shear waves, for example, are readily generated by EMATs. An EMAT system is very similar to the pulser/receivers used with PZT transducers and is therefore reliable, convenient to use, and easy to set up. The transducer itself, if mass produced, may be extremely inexpensive.

EMATs are not without its drawbacks. Since the technique is dependent upon inducing an eddy current in the sample, the transducer must be placed within close proximity to the sample surface. For highly precise time-of-flight or amplitude measurements, the transducer spacing, or lift-off, must be carefully controlled since it affects the generated and received waveforms. Currents within the coil, although fully enclosed within the transducer housing and generally of short duration (a few microseconds), may be on the order of several amps or higher, given the material under interrogation and the required signal-to-noise level. Unlike optical techniques, the transducer size may be of concern, depending upon the specimen geometry and the application (EMATs are typically as large as piezoelectric transducers, having diameters on the order of 0.5" or greater). Due to practical constraints in reducing the coil spacing, EMATs are generally limited to longer wavelength (several millimeters) pulsing and receiving. For shear waves in steel, for example, frequencies much higher than 1 MHz are difficult to achieve.

Laser Ultrasonics (LU)

Laser Ultrasonics refers to an advanced optical method for generating and detecting ultrasound. A variety of optical techniques are available for exciting ultrasound, the

Figure 2: a) Ultrasound generation via a laser source in the thermoelastic regime - a small volume (shaded region) suddenly expands elastically due to thermal heating, launching Rayleigh waves and angled bulk waves. b) Laser generation in the ablative regime - the recoil force from material ejected from the surface due to ionization initiates high amplitude Rayleigh and bulk waves in the specimen.

simplest being the thermal effect caused by a single laser pulse [3]. In the thermoelastic regime, the heat deposited by a short (15 ns) pulse of laser light causes a sudden expansion of the material, thus launching an elastic wave, typically in the ultrasonic frequency range (Fig. 2a). Afterwards, the heat dissipates and the material returns to its previous state unchanged. At very high light intensities, it is possible to generate ultrasound by ablating the material. The ablation regime, as it is commonly called, is characterized by material ionization, a process very similar to that used in spark spectroscopy (Fig. 2b). Ultrasound is created by the recoil action caused by the ejection of plasma from the surface. Although the strength of the ultrasound is significantly greater, operation in the ablation regime is clearly undesirable due to the visible surface damage (3-5 μm depth) which accompanies this process.

Laser detection is a somewhat more complicated process. Since a mechanical wave is associated with particle motion (which often manifests itself as a surface displacement), optical techniques sensitive to such motion may be used as an ultrasonic transducer. Several means are available, ranging from phase interferometry, which measures surface displacement (e.g. a Michelson design), to laser Doppler velocimetry, which captures surface velocity information [4]. Optical detection of ultrasound offers significant benefits, including high signal fidelity and absolute (calibrated) measurements, but are not without its shortcomings. Sensitivity to surface roughness and room vibrations are perhaps the most notorious. In addition laser systems tend to be rather complex when compared with conventional ultrasonic systems. Laser safety issues must also be dealt with since the powers used may be capable of causing damage to eye and other human tissue.

LU is a remote technique in the sense that the lasers and associated optical components may be located at a distance from the specimen. One practical consequence of this remote nature is that the technique can be used for applications with awkward or limited access and for specimens with complex shapes (e.g. a GTS reservoir). The directivity and frequency distribution of laser generated ultrasound may be tailored via the temporal and spatial pulse shape in order to achieve specific results. Absolute values for surface displacement or surface velocity are attainable with laser detection instruments, solving calibration problems associated with conventional ultrasonic inspection.

Despite the obvious benefits afforded by a fully-optical system, laser ultrasonics has yet to see widespread use in the industrial arena due in part to its lower sensitivity compared to conventional contact or immersion-based techniques [5]. Many approaches are available

for improving the received signal strength, the most obvious and undesirable being the use of higher power lasers for excitation and detection. Not only are bigger lasers more expensive and difficult to package, an upper bound for the power level is set by the material's ablation and annealing thresholds. This limitation represents the main challenge for a laser ultrasonic approach to become viable and the central focus of the LU development work for this project.

Frequency Response Method (FRM)

FRM is an empirical technique which has been widely-used over the years within the nondestructive evaluation (NDE) community and the sound and vibration industry [6]. When properly excited by a broad band input, an object vibrates in a unique manner which is dependent upon all aspects of the mechanical structure, including its shape, material, stress state, contents, and supporting fixtures, to name a few. Changes in any of these parameters, such as a relief in material stress, or even the presence of minor cracks and flaws [7, 8], will alter the vibratory signature. Similarly, however, the manner in which the structure is supported when the measurement is taken is also a factor which affects the acquired signal. Since the original FRM signature is empirical in nature, the results may be difficult to interpret; that is, FRM cannot easily separate specific elements from the entire physical system. In certain cases, it is possible to associate features in the FRM signature with a definitive cause.

FRM has been implemented in a variety of configurations using both contact and non-contact means for excitation and detection. A mechanical exciter (e.g. tapping a section with a hammer or ball bearing) is the simplest method for imparting energy to an object. This is often done for large structures which require a considerable amount of energy in order to excite the longer wavelength modes. Depending upon the frequency range, a microphone or an accelerometer placed on the object may be used to capture the dynamic response. A fully non-contact system consists of a white noise audio source and a laser vibrometer for measuring surface motion. Differences will then be observed in the power spectra of the acquired waveforms. Depending upon the required accuracy of the measurement, the mechanical exciter may be instrumented with accelerometers in order to normalize the results with the input energy.

III. EXPERIMENTAL RESULTS

Measurement of material stress based on the acoustoelastic effect relies upon accurate determination of wave velocity. This is typically accomplished by timing the propagation

of a wave over a known, fixed distance. If two detectors are available, or if multiple echoes are present, precise triggering is not necessary; as long as two or more signal pulses are captured by the digitizer, velocity determination is self-referencing with the resolution of the measurement being at least on the order of the digitization rate, provided the acquired waveforms do not change signal shape (i.e. dispersion). Signal processing may then be used to further improve the resolution. Stable triggering becomes a concern, however, if only a single detector is available. In this case, timing must coincide with the actual initiation of the elastic wave. The stability of the triggering source, then, directly affects the measurement error.

Emphasis was placed on using EMATs first to demonstrate the ultrasonic measurement of stress and then to devise an approach utilizing ultrasound for determining the fill state of GTS reservoirs. While EMAT interrogations do not run the risk of compromising the structural integrity of the component, a pulsed laser source is capable of material ionization and plasma generation. Before an attempt could be made to implement the technique using a fully optical system, the use of laser powers well below even the annealing threshold had to be ensured. While the measurement of the acoustoelastic effect was demonstrated using LU, technique development largely focused on maximizing the ultrasound amplitude while minimizing laser powers to levels at least an order of magnitude below the experimentally determined ablation threshold.

Figure 3: EMAT transducers were placed at the central weld portion of GTS-1. The transmitter is labeled "T" and the receiver is labeled "R".

Figure 4: Signal trace of an ultrasonic shear wave generated and detected using EMATs.

EMAT results

A 200 kHz shear wave, which traveled the circumference of the development bottle GTS-1 in both directions, was excited by an EMAT transmitter. As shown in the photograph of the experimental setup (Fig. 3), both the transmitter and receiver were placed at the central weld portion of the bottle. Figure 4 is a trace of the received signal propagating in GTS-1.

Figure 5: Comparison of EMAT signals for GTS-1 pressurized at 0 and 10 ksi.

The first pass underneath the EMAT receiver from each direction around the bottle occurs at approximately 30 and 45 μ s. Successive revolutions around the bottle are detected every 62 μ s thereafter. EMAT signal traces for GTS-1 with internal pressures of 0 and 10 ksi are compared in Figure 5. Since these measurements are made on the same reservoir, the change in wave arrival time is the noticeable effect of increasing the internal pressure. As shown in Figure 6, the delay change is linear with respect to pressure and hence material stress, as predicted by theory. The 490 ns change in propagation time between 0 psi and 10,000 psi for the shear wave traveling one revolution of the reservoir is comprised largely of a decrease in wave velocity due to the acoustoelastic effect (82%) and a smaller component resulting from the increase in path length due to material strain (18%). For comparison's sake, the path length uncertainty due to the machining tolerance specification of ± 0.005 in. for the diameter of GTS-1 translates into 32% of the total observed change in time-of-flight. Even under the worst case scenario, ultrasonics is capable of determining the fill status of the reservoir.

The development bottle GTS-1, two pairs (Helium filled and unfilled) of W87 deuterium bottles, and a B83 SP992 bottle were measured using a shear wave EMAT set. For GTS-1 and SP992, internal pressures were increased from ambient up to 10 ksi. Data was taken using both shear wave and Rayleigh wave EMATs at 2.5 ksi intervals. Signal traces from two W87 bottles which were previously filled and sealed were compared against two which were not filled. In all cases the measured change in wave arrival time fell within the expected error range of the theoretical predictions (when comparing the W87 reservoirs,

Figure 6: Relationship between delay change and internal pressure. Measurements were taken every 2.5 ksi.

dimensions and tolerances specified by the drawing were used for the theoretical calculations). It is noteworthy to mention that although a decrease in signal strength was observed when measuring the W87 bottles with the polyolefin heat shrink wrapper, the covering did not affect the final results.

LU results

As mentioned above, laser generation of ultrasound typically operates in one of two regimes: thermoelastic and ablative. Since the ablation threshold is dependent not only upon the host material but several other factors such as the surface finish, the optical frequency of the excitation laser, and the focused energy density, a study was performed in an effort to quantify the relationship between energy density and the amount of resulting surface damage. Samples of 304L stainless steel, machined to surface finishes similar to GTS bottle specifications, were irradiated with 15 ns laser pulses at a wavelength of 1.064 μm . Energy densities were varied between approximately 10 J/cm² and 150 J/cm². The ablation threshold for 304L SS was experimentally determined to be roughly 10 - 15 J/cm².

At high energy densities (above ~ 50 J/cm²), enough material was ablated such that profilometer traces clearly identified the surface depressions and ridges surrounding the ablated area (Fig. 7a). At lower energy densities, the blemish caused by the laser, although visible by eye, is obscured by the machining grooves (Fig 7b). Even if no material is removed from the surface, it is conceivable that the input of energy with densities near ablation may result in local annealing or microstructural changes. Optical metallographic inspection of cross-sectioned samples which were irradiated at energy densities under 100 J/cm² revealed no discernible difference between the irradiated spots and the surrounding

Figure 7: a) Profilometer traces of laser-irradiated samples at an energy density of ~ 100 J/cm². The depression and surrounding ridge of redeposited material due to ablation is evident. b) Ablation is still occurring at a lower energy density of ~ 20 J/cm², but its effect on the surface is obscured by the natural surface profile.

Figure 8: Signal traces capturing the Rayleigh wave arrival in 304L SS samples. The delay change in the arrival time is due to the imposed stress in the material.

area. Other inspection techniques such as electron microscopy, which are able to detect changes on the atomic scale, were not used. Since the volume being heated by the laser reaches only a few micrometers in depth for metals, it is not surprising to find that even for pulses with energy densities greater than the ablation threshold, microstructural aberrations above that which is normally present due to the manufacturing process are not created.

Measurement of the acoustoelastic effect using a fully optical ultrasonic system was first demonstrated on 304L SS samples stressed in a compression stand (see Fig. 8). Since a planar surface allows the experimental setup to be configured such that the path length remains fixed, strain was not a factor; the delay change exhibited is therefore solely attributable to the acoustoelastic effect. (Note that the compression stand stresses the sample uniaxially. Also, stress uniformity cannot be assumed in this case since the sample is under compression.) Before any measurements were taken from pressurized units, several improvements to the experimental setup were made which reduced the energy density to below 0.1 J/cm^2 (two orders of magnitude below ablation) while maintaining a sufficiently high signal-to-noise ratio. The replacement of the final spherical focusing lens with a cylindrical lens, which changed the source from a spot into a line, along with the use of a shorter optical excitation wavelength (532 nm), represent the two main modifications which resulted in the increase in the opto-acoustic conversion efficiency of the LU system. Although line sources distribute the available optical energy over a larger area, thereby reducing the amount of heat deposited per unit volume, the resulting ultrasound is directed into two narrow beams perpendicular to the line. This concentration of ultrasonic energy

Figure 9: Power spectra of the overall response of GTS-1 recorded by an audio microphone.

results in nearly the same signal amplitude. The second improvement mentioned above was largely driven by empirical observation within the LU research community that optical generation in metals is more efficient at shorter laser excitation wavelengths, especially in the ultraviolet range [9].

Ultrasound was then generated and detected at the weld section on GTS-2. Although a change in delay was observed when the reservoir was pressurized to 1,800 psi, attempts to implement the technique devised using EMATs were unsuccessful due to the inability of the laser source in generating ultrasound with sufficient amplitude to propagate the circumference of the reservoir. Without a second signal to serve as a reference and to ensure a fixed path length, difficulties arise in determining the actual distance traveled, a necessity for ascertaining wave velocities. Work to further improve the acoustic coupling from a laser heating source is ongoing. The addition of a frequency-doubling crystal to the source laser will allow UV radiation at 266 nm to be used in the experiments.

FRM results

Two sets of experiments were performed to assess the applicability of FRM. For both experiments a steel ball bearing dropped from a height of two inches served as the excitation mechanism. The overall response of GTS-1 was recorded by a dynamic audio

Figure 10: Power spectra of a single point measurement of surface velocity versus time made using a laser Doppler vibrometer.

microphone. Figure 9 is a portion of the power spectrum calculated from the response of GTS-1 at five pressure levels. Note that the zero power level for each trace has been shifted for clarity. Two strong peaks near 5 and 6 kHz are shown to emerge as the pressure is increased up to 2,000 psi while the overall spectrum under 10 kHz remains essentially unchanged.

A commercial laser Doppler vibrometer was used for the second set of measurements. Unlike the signal acquired by an audio microphone, a laser vibrometer is sensitive to surface velocities at a single spot. Therefore, depending upon the location being illuminated by the laser, different results may be obtained for the same vibration pattern. The power spectra shown in Figure 10 compares three dynamic responses, each under a different set of static conditions. While the data shown in Figure 9 were all taken with GTS-1 connected to a high pressure nitrogen source, the solid trace in Figure 10 is the response of the reservoir by itself. It is interesting to note that by simply attaching a pressure line to the stem of the reservoir, several resonances appear (e.g. at 1.2 kHz) and disappear (e.g. at 1.9 and 4.5 kHz).

V. DISCUSSION

The use of ultrasonics to determine the stress state of pressure vessels was shown to be viable in a laboratory environment. For 304L SS under tensile stress, acoustoelasticity was found to be the dominant factor affecting the propagation speed of shear and Rayleigh waves. The combined effect of stress and strain was large enough to offset the uncertainty due to machining tolerances; individual baseline traces for each bottle are not needed. Several other parameters, however, are also known to affect ultrasonic wave speeds, namely the material microstructure (e.g. crystallographic texture [10]) and the bulk temperature. While changes in microstructure is not a consideration for comparative measurements of a single bottle at different fill levels, temperature variations cannot be ignored. Hysteresis as large as 29% of the total delay change, for example, was observed during runs where gas was being added to and vented from the reservoir (this variation decreased considerably when the measurements were taken after pressure equilibrium was reached). While this observation is believed to be the effect of temperature, controlled experiments have not yet been performed to verify this hypothesis. If temperature is found to be significant factor affecting wave speed, a calibration table may be used to directly offset or eliminate this error source.

An implied feature of an ultrasonic stress measurement based on the acoustoelastic effect is the ability to provide quantitative values for the material stress. As shown in Figure 6, the linearity of the data is evident, even when temperature effects have not been taken into consideration. If a reference trace is available for a given reservoir, all unknown material parameters (e.g. true dimensions, residual stresses, material homogeneity) will be embedded within this reference measurement and will therefore no longer be a source of error. The attainable resolution, then, approaches the measurement's repeatability. When GTS-1 is used as an example, a ± 10 ns uncertainty in the time-of-flight calculation translates into ± 700 psi for the wall stress, or equivalently ± 200 psi for the internal pressure. On the other hand, if the path length is known to the machining tolerance of the component, only gross changes in material stress (e.g. > 10 ksi) can be detected. This does not present a problem for the application at hand since the purpose is solely to determine whether or not full venting of the reservoir has occurred.

While the feasibility of EMATs have been shown, concerns regarding the potential of high amperage pulsed currents and the presence of magnetic fields have been raised. As shown in Figure 4, the EMAT transmitter used for these measurements was capable of generating ultrasound which could travel several revolutions of the bottle. Since only one pass is

needed for the technique devised, a significant reduction in the input energy is possible simply by using the minimum current needed for the measurement. Additionally, the transducer used for these experiments was designed for applications involving ultrasound propagation in flat metal plates. Optimization for the curved surface of a reservoir will further reduce the peak amperage applied to the wire coil. Development of a prototype EMAT system is the next task to be addressed. Careful consideration to the design of a limited energy source and delivery mechanism will ensure that nuclear safety and reliability requirements are met.

The EMAT method requires the elastic wave to propagate at least one full revolution of the reservoir which in turn eliminates alignment and timing errors. A similar technique for measuring the acoustoelastic effect has not yet been adapted to an optical system primarily due to the low amplitude of the generated ultrasound. As mentioned earlier, acoustic coupling in metals using UV laser radiation has been observed to be more efficient than visible and IR sources. While frequency-doubling the 532 nm laser line to 266 nm will allow experiments to be performed using a UV source, the optimum laser frequency for use with 304L SS is ideally found through the use of an optical parametric oscillator (OPO) which provides continuous wavelength selectivity over broad frequency ranges. Unfortunately, an OPO was not available for this investigation. If it is not possible to excite an elastic wave with sufficient strength to propagate the required distances, alternatives are available but necessarily increase the cost and complexity of the system. Surface waves in excess of 50 dB signal-to-noise, for example, have been generated using a scanning interference fringe technique [11]. While a fully optical system is attractive, hybrid laser/EMAT configurations which exploit the benefits of each technique are another option which holds promise and may also be considered. Using a laser source eliminates the input amperage concerns associated with an EMAT transmitter whereas a broadband EMAT receiver is typically more sensitive and significantly less complex than an optical interferometer.

Figures 9 and 10 indicate that differences between filled and unfilled reservoirs may be observed using the Frequency Response Method. Although the data presented appear encouraging, FRM implementation may not be feasible without a capability which would allow response curves to be predicted for a given reservoir geometry at various internal pressures. Since FRM is itself empirical in nature, the selection of resonance modes upon which the determination of fill state is assessed becomes a difficult task, especially in view of the response spectra presented in Figure 10. Since the modal resonances are highly

sensitive to the boundary conditions and depend upon the entire mechanical system, it may not be possible to devise a valid technique without collecting data from pressurized components which have been installed in their natural environment (i.e. within weapons systems). Pursuit in this area should be focused on the development of numerical models which can predict resonance spectra for complicated geometries. If successful, experimental validation of these models will be needed, followed by a prototype instrument design for demonstration.

As stated above, several issues remain to be addressed for each of the proposed ultrasonic generation and detection methods, including the ability to meet nuclear safety and reliability requirements. Additionally, the effect of secondary parameters such as temperature, residual stresses, and material homogeneity on the ultrasonic wave speed itself needs to be quantified in order to establish general performance specifications of an ultrasonic approach. The next phase of this investigation, then, will include a requirements analysis (product performance, programmatic, logistics and support), experimental validation tests, and a conceptual design of a prototype instrument at a time and effort level concomitant with work performed for this feasibility study. Detailed design, fabrication, and testing may then follow if all requirements are met.

CONCLUSIONS

The use of ultrasonics for the measurement of pressure vessel wall stress has been demonstrated. A technique using electromagnetic acoustic transducers based on the measurement of the acoustoelastic effect has been devised which can positively identify the fill state of a reservoir with known dimensions. Calculations using typical machining tolerances indicate that an initial reference measurement for each reservoir is not needed; only the nominal dimensions are required for a particular reservoir design. Laser ultrasonic measurement of stress was also demonstrated. Low ultrasound amplitudes, however, prevented the EMAT technique to be adapted to LU. Further optimization of the ultrasound generation mechanism is needed before an optical approach is feasible. When the frequency response method was used, distinct frequency and amplitude changes were observed in the resonance peaks when the reservoir was subjected to various pressure conditions. Signatures obtained using this method, however, was found to be highly sensitive to its input parameters. Predictive capability, as well as experimental validation of these models, is required for this technique to be applicable over the wide range of reservoir designs and operating pressures that will be encountered.

ACKNOWLEDGMENTS

The authors would like to thank Andy Gardea, Darcy Hughes, and Nancy Yang for helpful discussions and their involvement in the metallographic study of the laser-irradiated samples, and Mike Hardwick, Leon Seibel, and John Korellis for their continued assistance throughout this project.

REFERENCES

1. W. Y. Lu, C. S. Man, "Measurement of stress based upon universal relations in acoustoelasticity," *Experimental Mechanics*, Vol. 29, 109, 1989.
2. B. W. Maxfield, C. M. Fortunko, "The design and use of electromagnetic acoustic wave transducers (EMATs)," *Materials Evaluation*, Vol. 41, 1399, 1983.
3. C. B. Scruby, R. J. Dewhurst, D. A. Hutchins, S. B. Palmer, "Laser generation of ultrasound in metals," *Research Techniques in Nondestructive Testing*, Vol. V, 281-327, London: Academic Press, 1982.
4. J. W. Wagner, "Optical Detection of Ultrasound," *Physical Acoustics*, Vol. XIX, 1990. Academic Press, New York, NY.
5. J. W. Wagner, "Breaking the sensitivity barrier: the challenge for laser-ultrasonics," IEEE Ultrasonics Symposium, 1992.
6. P. Roth, "Effective measurements using digital signal analysis," *IEEE Spectrum*, April 1971.
7. T. F. Drouillard, D. K. Gustaveson, D. N. Ikle, "Nondestructive evaluation of precision parts by frequency response testing," 59th Shock and Vibration Symposium, Albuquerque, NM, Oct. 1988.
8. D. K. Gustaveson, "Direct parameter identification from frequency response measurements," *Proceedings of the 5th International Modal Analysis Conference*, London, England, Vol. II, 1352, 1987.
9. Private communication with R. Bernier, Ultra-Optec, Inc., Boucherville, Quebec.
10. W. Y. Lu, S. L. Min, "Effect of wave types on ultrasonic texture determination," *Review of Progress in Quantitative Nondestructive Evaluation* (in press).
11. H. Nishino, Y. Tsukahara, "Excitation of high frequency surface acoustic waves by phase velocity scanning of a laser interference fringe," *Applied Physics Letters*, 62 (17), 2036, 1993.

Initial Distribution:

MS9001	Tom O. Hunter	(08000)
MS9004	Mim E. John	(08100)
MS9005	Jim Wright	(02200)
MS9006	Don Bohrer	(02203)
MS9013	Bob Anderson	(02266)
MS9013	Bill Delameter	(02266)
MS9013	Russ Miller	(02266)
MS9013	Shermann Min	(08111)
MS9013	Greg Thomas	(08111)
MS9014	Tom Harrison	(02271)
MS9014	Cook Story	(08115)
MS9015	Carolyn Pura	(02221)
MS9033	Corey Knapp	(02262)
MS9034	Dennis Beyer	(02263)
MS9034	Roger Everett	(02263)
MS9035	Robert Monson	(02264)
MS9036	Doug Henson	(02254)
MS9043	Jay Dike	(08742)
MS9044	Wendell Kawahara	(08746)
MS9044	Wei-yang Lu	(08746)
MS9401	Mike Dyer	(08700)
MS9404	Larry Peng	(08713)
MS9404	Jim Wang	(08713)
MS9407	Ed Cull	(08415)
MS9407	Mike Hardwick	(08415)
MS0490	John Hoffman	(12331)
MS0492	Daniel Summers	(12332)
MS9021	Technical Communications Department, 8535, for OSTI (10)	
MS9021	Technical Communications Department, 8535/Technical Library, MS0899, 13414	
MS0899	Technical Library, 13414 (4)	
MS9018	Central Technical Files, 8523-2 (3)	