6th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components
October 2007, Budapest, Hungary

Other Major Component Inspection I

Application of Guided Waves Technology for Screening of SeaCure Tubing

N. Muthu, EPRI, USA; S. Vinogradov, IHI Southwest Technologies Inc., USA

ABSTRACT

Guided waves (GW) can be a very cost-effective technique for long-range piping and tubing inspection. One of the most pronounced advantages of GW is that the technique is capable of covering 100% of the component volume in a very short time. The work described in this paper was an attempt to investigate GW applicability for fast screening of SeaCure condenser tubing. Besides the regular task of identifying metal loss areas, two specific tasks were targeted: detection of defects located under tube support plates (TSP) and detection of small volume axial cracking. Both tasks have been found to be very difficult to accomplish using established, conventional NDT techniques.

Two types of probes, utilizing magnetostrictive Joule and Villary effects, were developed by ISWT. Both allow fast, non-contact generation of ultrasonic wave in the tube wall. One type of probe was designed to send and receive from the end of the tube for the detection of metal loss areas together with the detection of defects located under the TSPs. Another type of probe is a "pull through" type of probe. This probe was designed to propagate an ultrasonic wave circumferentially, for the purpose of the detection of small volume axial cracking. A number of operating frequencies from 32 to 250 kHz were tested with the best performance achieved at the higher frequencies. Both torsional and longitudinal waves were used and shown to be successful for detection of different types of flaws.

The probes were tested on a mockup bundle representing a condenser, simulating different kinds of damage including corrosion pits, wear, fretting, and both axial and circumferential cracking. All flaws were successfully identified when the results of both probes were combined. No significant interference from the TSPs was observed, which implies that there is a rather high probability of detection of flaws in the TSP areas.

Further work will be focused on testing the GW probes in real conditions to identify the available inspection ranges, the speed of the inspection, and possible limitations.

INTRODUCTION

SeaCure alloy has been considered as one of the rather promising materials for use in condensers because of its high resistance to corrosion. However, there are still a number of mechanisms causing the damage of the tubing primarily due to metal loss and cracking. Now there are a number of conventional techniques for inspection of the tubing utilizing electromagnetic and ultrasonic methods. However, they still have limitations such as relatively low inspection speed and limited sensitivity to small volume cracking. Areas under TSP have also been found to be difficult for examination due to the distortion of magnetic fields caused by TSP[1].

Using GW for long-range inspection of components has proven to be a very cost effective approach for the number of applications.[2,3]. Since GW can cover the entire volume of the tube in a matter of seconds, the method has been considered a valuable complimentary asset to conventional methods of the inspection. However, due to rather high complexity of GW scattering phenomenon, every particular application requires additional investigative efforts to clear up the question if GW can meet the criteria of sensitivity and reliability of detection. As an example, one of the most challenging problems regarding screening of heat exchanger tubing using GW was the presence of the non flaw-related responses produced by tight TSP crossings. Assuming there is a rather high probability to encounter the same sort of problem in condensers, significant attention was given to any solution helping to minimize the influence of the phenomenon. Optimization of the processing and the interpretation of acquired data was another considerable part of work scope determining cost effectiveness of the technology.

The work presented was supported by EPRI and conducted by IHI Southwest Technologies, Inc. with the purpose of production and evaluation of a field inspection probe using GW.

CONCEPT OF SCREENING USING GUIDED WAVES

The concept of rapid screening of tubing using GW has utilized the capability of GW to travel long distance in the components without essential attenuation. Initial impulse can be generated from the single spot typically within a range 1 to 3 feet from the end of the tube by inserting the probe as it is shown on Figure1(a).

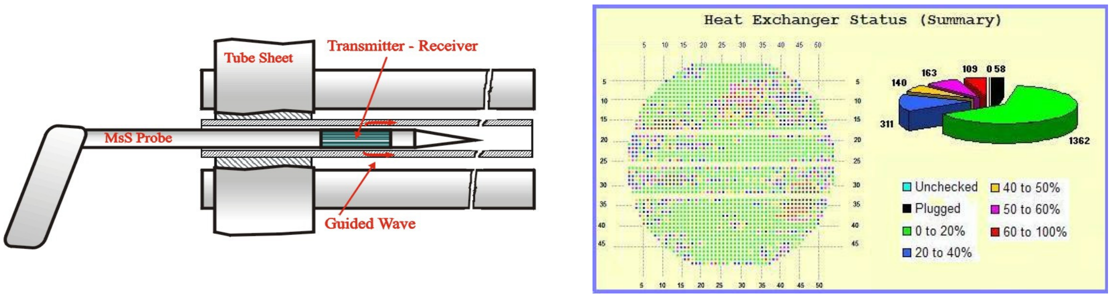


Figure 1 - Concept of screening using GW:
(a) positioning of the probe in the tube, (b) example of a summary report

Mechanical vibrations producing GW can be generated in the probe and then interrogated into the wall by mechanical coupling[4,5] or they can be generated directly in the tube wall using different electromagnetic techniques[6]. Taking into account that no tube cleaning is needed, the whole data acquisition process per tube takes 10 to 30 seconds, depending on the screening mode, and is described below.

Sensitivity of GW waves depends on a number of parameters such as type of defect (volumetric or crack), geometry of the defect (including all three dimensions), and the condition of the tube. There has been a great deal of investigative work done about defect sizing using GW,[7,8,9] but the technology is still a great distance away from an accurate assessment of the remaining wall thickness under flaws. This is the main reason why the whole approach has been considered more appropriate for screening rather than for the inspection. However, even in screening mode there is still a great demand, as well as potential, for possibly more informative assessment of the condition of the tube without reducing the production speed. Implementation of the screening approach should allow moving from the concept of taking a random number of samples during the inspection (typically 10 to 15%) to screening of 100% tubes with following mapping of the screening results. Based on screening, inspection efforts can only be addressed to the tubes or to the areas of condenser with reported problems (an example of a screening summery report is shown on Figure1(b).

PROBE DESIGN AND PRINCIPLE OF OPERATION

As mentioned above, generation of GW in the components can be accomplished in two ways: by generating mechanical vibrations in the probe with further interrogation of the energy into the wall by mechanical coupling or by generating mechanical vibrations directly in the tube wall by using electromagnetic techniques. Mechanical coupling provides the advantage of screening any tubes regardless of the type of material while electromagnetic techniques (based on magnetostriction) have been bounded to ferritic alloys. However, electromagnetic generation (if possible) has been proven capable of providing both high signal quality and an outstanding signal directionality control regardless of the condition of the internal surface of the tube. Another advantage of the method is the capability of generating perfect axially symmetric waves or non-axially symmetric waves depending on the distribution pattern of bios (permanent) or variable magnetic fields. Since SeaCure alloy allows electromagnetic generation of GW, the probe utilizing Joule-Villary effect for generation and receiving of GW was developed, see Figure 2(a).

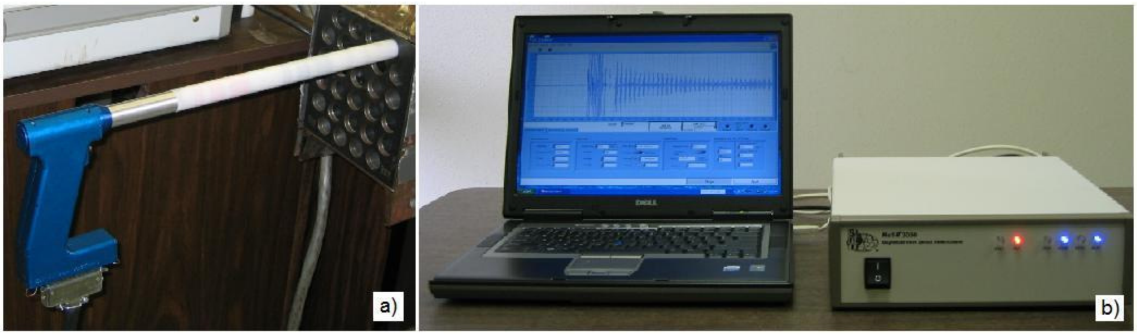


Figure 2 - GW probe (a) and MsS Instrument (b)

The probe coils were driven by a MsS instrument developed by Southwest Research Institute for a variety of applications using GW, see Figure 2(b).

Special attention was given to selection of the mode of GW. Both torsional and longitudinal modes of GW were tested on the mockup with somewhat better signal to noise ratio (SNR) achieved using L(0,2) mode of GW. Another advantage of the selected mode of GW was the response obtained from the simulators of tight TSP crossings was about 6 dB lower. The comparison was made using 250 kHz of L(0,2) mode and 125 kHz of T-mode that allowed any discrepancy caused by unequal wavelength of the pulse to be minimized. A well known disadvantage of longitudinal mode of GW associated with higher dispersion rate and with the concurrent presence of L(0,1) mode was found to be not as pronounced for the considered type of tubing and can be understood from the dispersion curves of the GW shown on Figure 3.

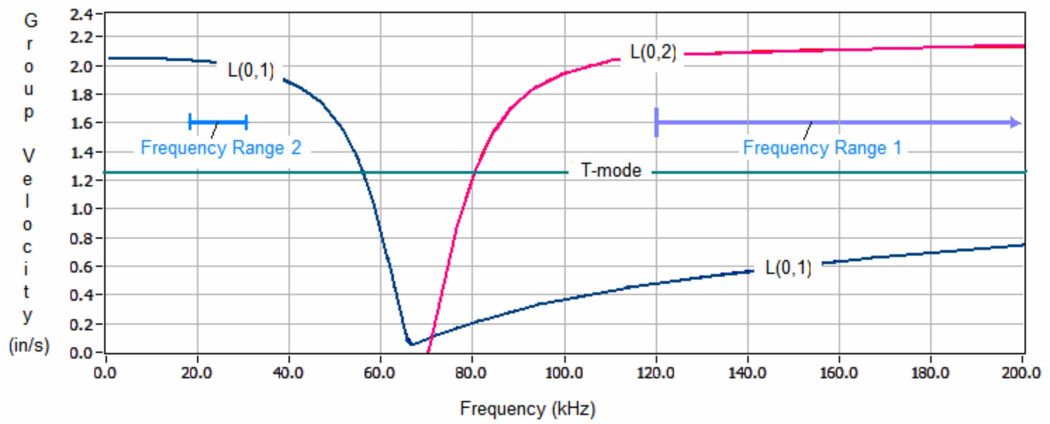


Figure 3 - Group velocity of different modes of GW in 1" OD SeaCure tubing

It can be noted that the group velocity of L(0,2) mode of GW in a frequency range of 120 kHz and up (Frequency range 1) is about three times higher versus the group velocity of L(0,1) mode that is also a good indicator of the corresponding energy of the pulses. If the condition of the tube introduces a high attenuation rate to the GW pulse, lower frequency range (frequency range 2 on Figure 3) can also be used. In that case, an incident pulse will be presented only by L(0,1) mode of GW, which has a rather low dispersion rate as well as high energy in the range 15 to 30 kHz. In practical application though, the lower frequency GW cannot provide as good sensitivity and axial resolution as GW with the higher frequencies.

A GW probe was initially tested in a range of frequencies on a 50 ft long SeaCure tubing mockup. Figure 4 shows the results obtained at 250 kHz using axially symmetric L(0,2) mode of GW. The data include three roundtrips giving a close equivalent to 150 ft long tube.

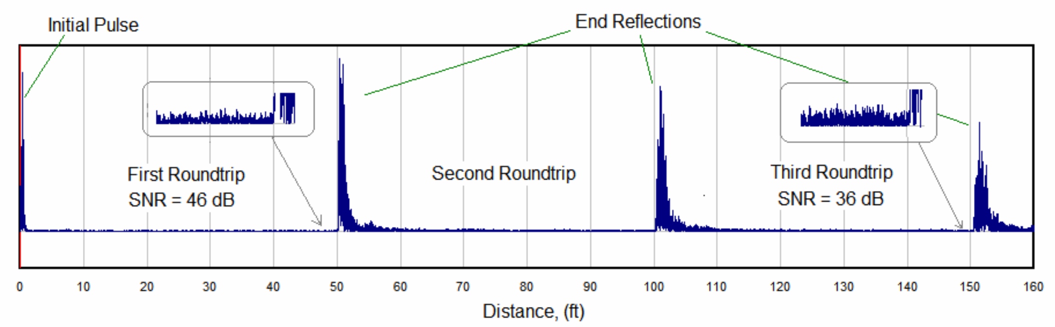


Figure 4 - Data obtained from clean 50 ft long 1" OD SeaCure tube

An attenuation rate with the selected frequency was found to be about -0.05 db/ft. Additional attenuation induced by TSP with the tolerances presented was found to be -0.0012 dB/TSP. On the first roundtrip, SNR was close to 46 dB, and by the end of the range, it moved down to 36 dB. In terms of the sensitivity, on the first roundtrip a detection of a defect as small as 1% compared to the cross-section of the tube would be possible. With the SNR at 36 dB, the threshold detection level would have to be 3% and up. Taking into account that the majority of condenser tubing has a length less than 120 feet, the technology has a potential to be sensitive to volumetric flaws as small as 2 to 2.5% ES by the end of the inspection range.

It should be noted that the noise level increments in larger steps when GW passes a strong reflector. In the example presented, the end of the tubes serves as such a reflector. In real conditions, just about every flaw tends to contribute to the level of the internal reverberation noise and an actual SNR can vary depending on the condition of each particular tube.

DATA ACQUISITION

Data acquisition procedure depends on the scope of the inspection and can be performed in two modes – a fast screening mode and a full screening mode. The major reason for using two acquisition modes is that the GW probe, like any other ultrasonic transducer, has a specific blind area called "dead zone" (DZ) and "near zone" (NZ). A general pattern of the signal strength in those areas is shown on Figure 5. In the NZ, GWs have limited sensitivity while DZs represent a blind spot. Depending on the operating frequency, combining extent of both zones can vary from 1.0 to 2.5 feet in the direction of propagation of the GW. Coverage of those zones requires taking two additional data sets from the same end of the tube but from different positions of the probe. As an alternative, data can be taken from the opposite ends of the tube, but this approach seems to be more practical for tubes with U-bends rather than for straight tubing.

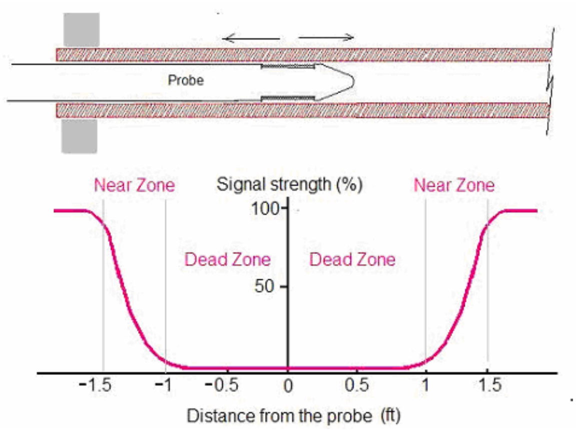


Figure 5 - General pattern of GW signal strength in DZ and NZ areas for 200 kHz probe

Figure 6 shows different options in the way the data can be acquired. In the fast screening mode, only one data set is acquired from the probe position '1' and by sending the signal in the forward direction '1', see Figure 2 (left picture). In that case, about 1.5 to 2.5 feet of the tube will be uncovered but the data acquisition time per tube can be around 10 seconds.

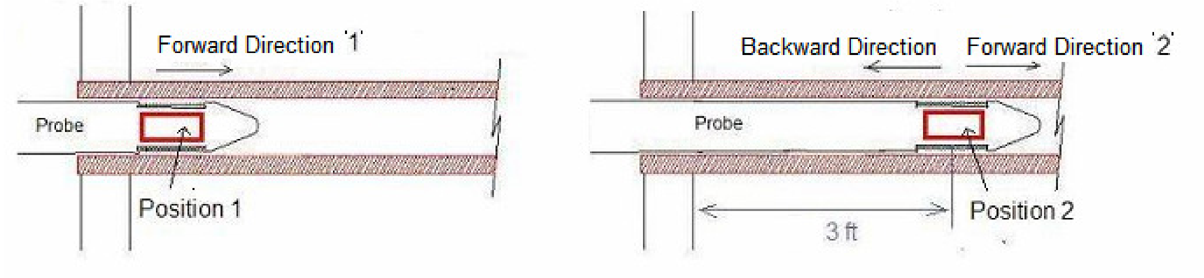


Figure 6 - Principle of data acquisition using GW probe: fast screening mode (left); full screening mode (left plus right)

In the full screening mode, DZ can be eliminated, but two additional data sets should be taken from the coil position '2'. One data set will cover the backward direction and another should be sent in the forward direction '2'. In real condition, there is no need to replace the probe in the tube and only switching between two sets of coils is needed. After combining the results, the data on the 'A'-scan will appear as it is shown of Figure 7.

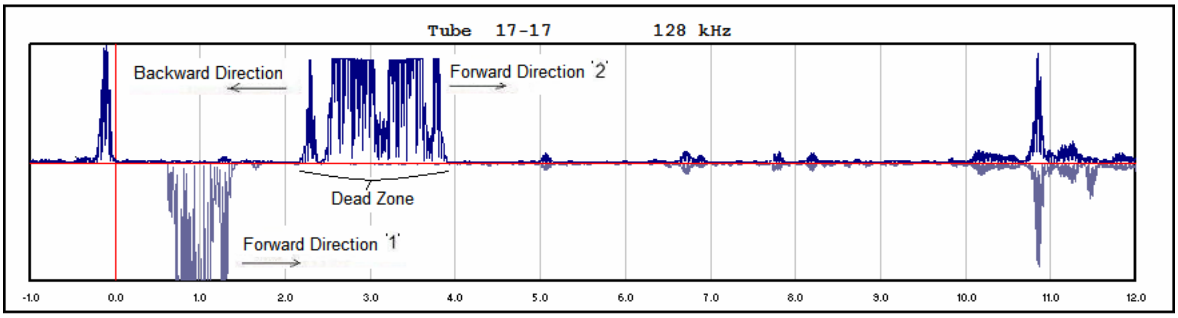


Figure 7 - 'A'-scan data after combining three data sets obtained in full screening mode

All the signals were rectified in plus or minus direction and placed on the chart in the way that the data from the forward direction '1' could back up the data from the forward direction '2'. It can be noted that this kind of view allows getting a confirmation for flaw indication. In the majority of cases if a response originated from real reflectors, then the response should look identically and stay in the same position regardless of the position of the probe. After finishing the analysis, data can be presented as shown on Figure 8 with DZs eliminated by combining different data sets.

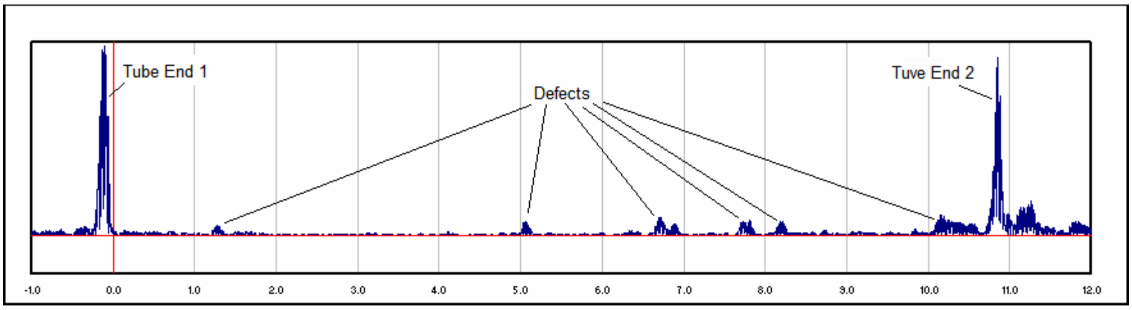


Figure 8 - 'A'-scan presentation with 100% coverage of the tube length

As it can be noted, both tube ends are presented on the chart with some flaw indications between them. Any of the reflections from the end of the tube can be used for the purpose of pre-calibration of all other responses as long as the reflection stays outside of NZ of the probe. Obtaining more accurate information about the depth of the flaw may require performing an assessment of both axial and circumferential extents of the flaw.

GW PROBE PERFORMANCE IN 1" OD SEACURE MOCKUP

To evaluate performance of the GW probe, a 6-foot long SeaCure mockup was provided by EPRI NDE Center with the number of flaws including simulators of metal loss, corrosion pits, TSP wear, and axial and circumferential cracking. All tubes were put together with the number of TSP manufactured with tolerances representing real conditions. Data were acquired in the full screening mode from 28 tubes including 13 blank tubes without defects. Flaws were machined with high precision and an effective size (ES) of each flaw was calculated as a ratio of the cross-section of the flaw to the cross-section of the tube.

With the tolerances presented in the mockup, no significant interference of GW with TSP was observed. In the blank tubes, 7 out of 52 TSP crossings (13% of the entire volume) produced responses equivalent to the response from flaws with 1 to 1.5% ES. Figure 9 shows a typical pattern of the response obtained from the blank tubes.

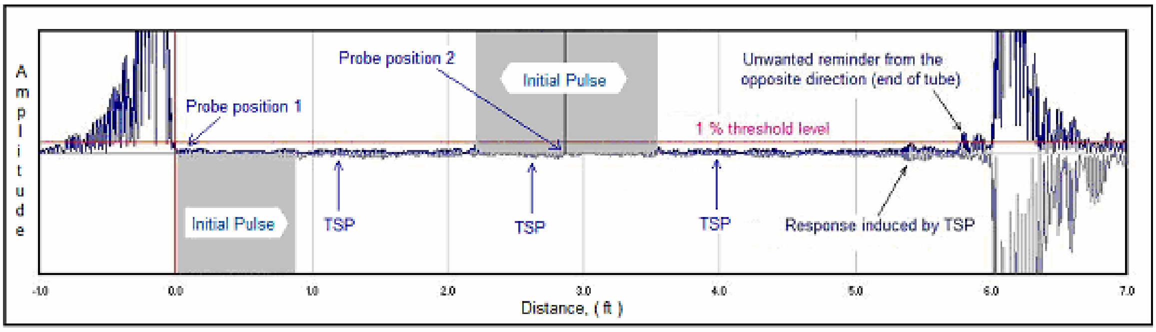


Figure 9 - Typical pattern of the responses obtained from SeaCure tubing containing no defects

As noted from the picture, the response produced by the last TSP is quite below the 1% threshold detection level. Overall, SNR was in the order of 46 dB. A supression rate of the signals from an unwanted direction was about -36 dB, which is considered to be a rather good control over the directionality of GW. With the SNR at 46 dB, detection of volumetric flaws as small as 1% ES is possible. However, defects with the volume close to "zero" produce a rather unique pattern of GW scattering, and detectable size of the defect was found to be essentially larger compared to the volumetric flaws. Both axial and circumferential cracking represent defects with close to "zero" volume, and axial cracks also represent flaws with 0% ES. As an example, Figure 10(a),(b),(c) shows data obtaned from tubes with different type flaws: volumetric flaws (a), circumferential notches (b), axial notches (c). In the data presented, volumetric flaws produced a rather clear response including simulators of OD pits with ES close to 1.5%. Responses from 'wear' type of damage produced a rather distinctive pattern with tailing signals, see Figure 10(a). ES of each flaw can be approximately identified based on the amplitude of the response. With the threshhold detection level established to 1%, it can be concluded that the OD pit can be rated as a 1.4% flaw. However, the presence of any large reverberation calls mixed in the signal can make an assessment of ES of flaws rather complicated. On the data set presented, a strong reverberation call can be observed at a distance 5.5 feet with the amplitude equivalent to 16% ES.

From Figure 10(b), it can be concluded that a circumferential crack with ES at 8% produced a response equivalent to 2% ES flaw. The phenomena is caused by a destructive interference between responses produced by the front and the rear edges of the notch and quite common for any flaws with sharp edges and small axial extent. The rest of the notches with larger ES were detected with good SNR.

Detection of axial notches was found to be rather complicated because such a flaw has 0% ES. However, in the presence of a rather deep notch (75% to through wall), a response from such a flaw can be observed with accompanying tailing signals, see Figure 10(c). The response by itself, together with tailing signals, was assumed to be produced by mode conversion of flexural components of GW to the plate Lamb waves and visa versa.

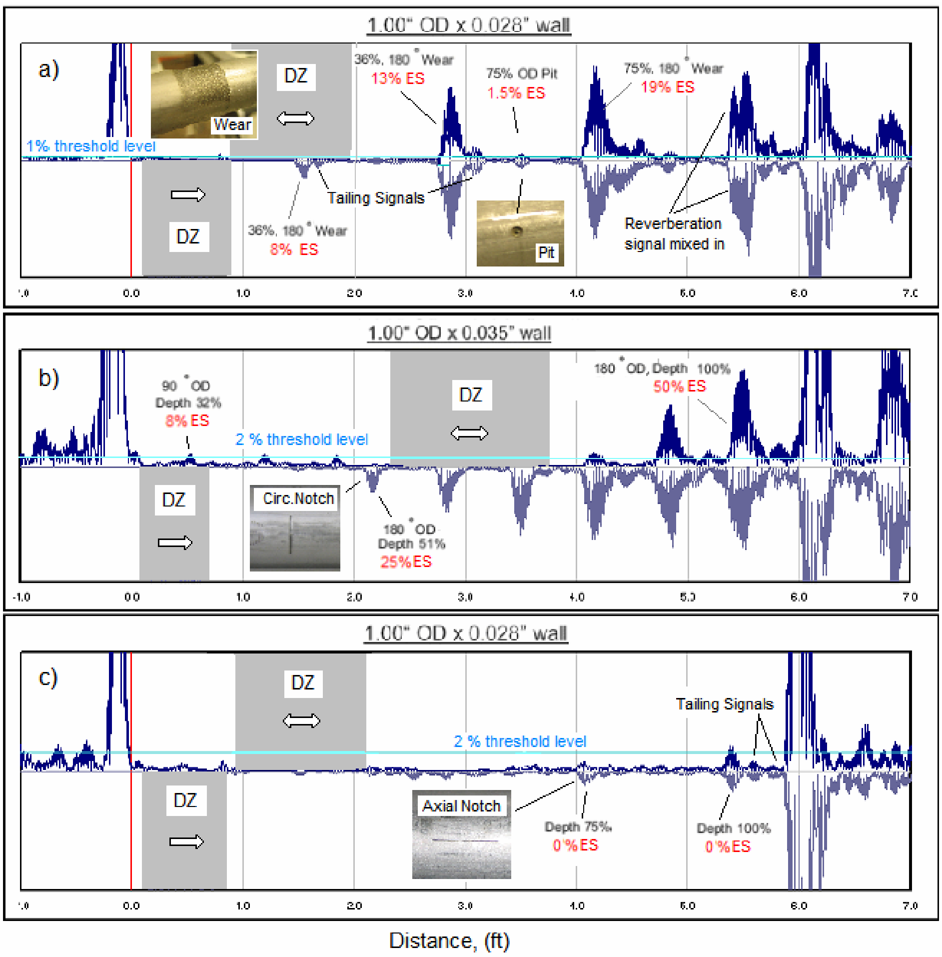
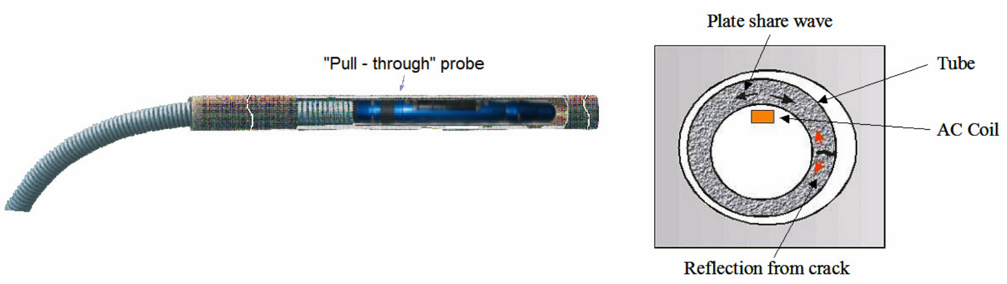


Figure 10 - Data obtaned from tubes with different flaws using L(0,2) mode of GW at 250 kHz:
(a) a tube with 8 volumetric flaws including wear and OD pits;
(b) a tube with 8 circumferential notches; (c) a tube with 8 axial notches

A similar phenomenon was reported earlier in application to detection of axial cracking using torsional mode of GW[10]. Compared to 'T'-mode of GW, 'L'-mode was producing much a smaller response from the same through-wall crack (2% ES with 'L'-mode versus 8% ES with 'T'-mode). However, neither mode of GW produced any noticeable response from axial notches with the depth less than 70%. Since even a 30%-deep axial crack represents a rather critical flaw, an alternative method of detection of such a condition was developed.

DETECTION OF SMALL VOLUME AXIAL CRACKING

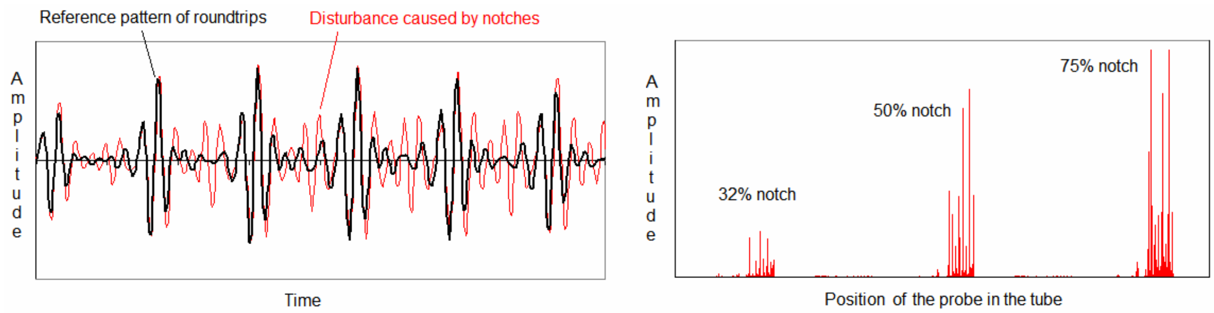
Reliable detection of small volume axial cracking (AXC) can be considered as a 'stand alone' problem for any kind of NDE technique available on the market today. As it was shown above, GW showed only limited sensitivity to flaws of that type. An alternative way of detecting such a defect is under development. The method utilizes plate shear waves (SW) traveling in the circumferential direction around the tube. A probe allowed electromagnetic generation and receiving of ultrasonic pulses in a range of frequencies 120 to 250 kHz. However, pulling of the probe through the length of the tube is needed to cover the entire volume. Figure 11 shows the concept of AXC detection using the share wave probe.



a) b)

Figure 11 - Plate SW probe: (a) "pull-through" type of instrument used for detection of AXC; (b) principle of operation of the probe

The probe generates a share wave traveling either direction around the circumference of the tube. In the presence of a tube in good condition, the wave crosses the receiver many times producing a rather steady roundtrip pattern shown on Figure 12(a). The pattern is stored in a memory as a reference signal. Any abnormal condition of the tube causes distortion of the roundtrip pattern and such a distortion can be tracked by the real time processing software. The processing algorithm takes into account both amplitude, phase shift and attenuation of the acquired signal and introduces the processed result on the 'real time' monitor (amplitude of the disturbance versus position of the probe) shown on Figure 12(b).



a) b)

Figure 12 - Detection of small volume AXC: (a) a disturbance induced to the reference signal by axial notch; (b) processed signal providing an indication of the severity of the disturbance produced by 32, 50, and 75% deep and 0.005" wide axial notches

From results of experimental evaluation of the probe, it was found that the probe was capable of detecting AXC with the depth at 32% and up at 250 kHz of SW. If the crack was located under TSP, the amplitude of the response was lower but cracks could still be detected when the probe was only approaching the problem area. The effect primarily existed due to a certain beam spread of SW in forward and backward direction from the AC coil. The disadvantage of the probe was a high sensitivity to any kind of flaws. Better determination of reasons causing the disturbance in the reference signal is needed. Another problem was associated with requirements of real time data processing that can put some limits on the speed of the inspection, which is presently limited to 1ft/second.

SUMMARY

From the experimental work described above, it can be concluded that in 1" OD SeaCure tubing, the majority of defects with ES 1.5% and up can be detected using 250 kHz L(0,2) mode of GW. Areas under TSP can also be covered.

Probability of the detection of small volume circumferential notches (cracks) with the effective size close to 10% is strongly dependent on the SNR and can be rather high if SNR is close to 46 dB. Indicated SNR was accomplished in tested 6-foot long SeaCure mockups as well as in a blank 50-foot long SeaCure tubing. An actual SNR in field application can vary depending on the condition of the tube. Detection of larger circumferential notches did not seem to be a problem.

Detection of small volume axial cracking was found to be rather difficult using GW. Only 75% of through wall notches produced responses equivalent to responses from flaws with 1 to 2% ES. Using a shear wave 'pull-through' type of probe was found to be effective for detection of such a cracking with a depth 32% and up.

Reflections from tight TSP in the mockup were found to be in the amplitude range from 1.0 to 1.5% ES and occurred in 13% of the total number of TSP crossings. In real conditions, if higher amplitude responses will be presented, a pattern recognition analysis could be utilized to recognize potential problems under TSP.

Using the described GW screening tool in a full screening mode should allow covering of the entire volume of the tube with a length up to 150 feet with the production speed at 30 sec/tube.

Obtaining more detailed information about the geometry of flaws using flexural modes of GW in conjunction with a multi frequency approach is considered promising and could be the subject for a future work.

REFERENCES

1. K. Krzywosz, N. Muthu. "Eddy Current Analysis of Relevant/Non-Relevant Signals from Tube Sheet Region of HP Feedwater Heaters", third International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, Seville Spain, 2001.
2. Alleyne, D. N., Pavlakovic, B. N., Lowe, M. J. S. and Cawley, P. (2001) "Rapid, long range inspection of chemical plant pipework using guided waves", Insight, Vol. 43, pp. 93-96.
3. H. Kwan, S. Kim, G. Light, "The Magnetostrictive sensor technology for long range piping guided wave testing and monitoring of structure", Materials Evaluation. 61: 80-84, 2003.
4. H. Kwan, J. Crane, S. Kim, A. Parvin, G. Light, "A torsional mode guided wave probe for long range in bore testing of heat exchanger tubing" Materials Evaluation. l: 430-433, 2004.
5. Vogt, T., Alleyne, D. N., Pavlakovic, B. N., "Application of guided wave technology to tube inspection", Insight, ECNDT 2006 - Th.3.1.5.
6. S. Vinogradov, G. Kidd, "Advanced guided wave piping and tubing inspection using magnetostrictive sensor technology", 5th International EPRI Conference on NDE in Relation to Structural Integrity of Nuclear and Pressurized Components, San Diego, California, 2006.
7. Rose, J. L., Sun, Z., Mudge, P. J., Avioli, M. J., "Guided wave flexural mode tuning and focusing for pipe inspection", Materials Evaluation, 61, pp. 162-167, 2003.
8. Demma, A., Cawley, P. and Lowe, M. J. S. (2003b) "The reflection of fundamental torsional mode from cracks and nothches in pipes", J Acoust. Soc. Am., Vol. 114, pp. 611-625.
9. S. Vinogradov, B. Jacobs, J. Godwin, "Experimental and theoretical investigation for the use of guided waves to detect and size corrosion/erosion defects in heat exchanger tubes", 7th EPRI Balance - of Plant Heat Exchanger NDE Symposium. June 17-19, 2002, Santa Ana Pueblo, New Mexico.
10. H. Kwan, S. Kim, H. Matsumoto, S. Vinogradov, "Detection of axial cracks in tube and pipe using torsional guided waves", QNDE Proceedings 2007 (to be published).