ULTRASONIC INSPECTION OF STEAM GENERATOR TUBING

BY CYLINDRICAL GUIDED WAVES

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BACKGROUND

In this paper we report on the experimental results demonstrating the potential of using cylindrical guided waves (CGW) for inspection of steam generator tubing (SGT). The CGW ultrasonic technique is intended to complement the present eddy current (EC) practice for in-service inspection as well as to provide an alternative tool for pre-service inspection. Below, we review the current NDE practice for SGT and the motivation of this study.

SGT is currently inspected primarily by various EC techniques, which have proven to be generally superior to other techniques in terms of scanning speed and reliable data interpretation. The EC techniques identify types of defects by recognizing a certain signal pattern, size the damage on the basis of the phase angle methodology, and select an appropriate frequency to target a specific type of defect. In addition, depending on the defect type of interest, different EC probes are used, ranging from the simple, fast bobbin coil to the more sophisticated array coil.

However, the EC data analysis procedures are not always capable of distinguishing all forms of damage. As a result, identification of a certain defect type is sometimes only achievable by inferring from its location. Difficulties are also encountered in attempts of sizing stress corrosion cracking and intergranular attack. But most important of all, the need for point-by-point scanning makes inspection of SGT by the EC techniques become a very time-consuming process. This is a key reason for us to explore the possibility of using the CGW's for inspection of SGT.

In a tubing geometry, there are two broad types of CGW's, one propagating along the axis and the other around the circumference. One subset of the axial CGW's are the elliptically polarized waves which are reducible to the classic Lamb waves in the limit of thin

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 9
Edited by D.O. Thompson and D.E. Chimenti
Plenum Press, New York, 1990

tubing. It is this type of CGW's that are considered in the present application. The most important advantage that one can get from these wave modes is the fact that they can propagate a long distance without significant attenuation loss. This exceptional characteristic allows us to expect that a CGW pulse can be excited from one end of the tube, propagates along its entire length and returns with information on possible reflectors in the tube. This inspection approach therefore would completely eliminate the need for point-by-point scanning and thus significantly reduce the inspection time. The principal question is whether one can excite the desirable CGW mode and locate, identify and size the typical defects in SGT from the reflected pulse train. In this experimental effort, we established the feasibility of the CGW technique on a comprehensive set of built-in artificial flaws that would best simulate the types of defects that are normally found in SGT.

EXPERIMENTAL APPROACH

First, let us review the types of defects normally found in SGT. Defects that threaten the structural integrity of SGT are of the following types:

- Wall thinning
- Pitting
- Primary side cracking
- Secondary side cracking
- Fretting
- Damage precursors such as magnetite build-up, tube denting, sludge pile-up and damaged support plates.

Most of the above defects are seen by the CGW pulse as reflectors of different sizes and shapes. In the present study, defect simulation was accomplished by introducing into the sample tube various artificial defects such as EDM notches, flat-bottomed holes and through-wall holes. Reflectors of a more complex shape are represented by simulated corrosion-induced pitting machined into the outside wall of a tube. The capabilities of the CGW technique was tested on a tube that contains an actual IGSCC crack as well as on an industry-standard calibration tube currently used for the EC techniques. Finally, CGW's were also excited in long tubes of 30 feet in length and in U-bend tubes to verify the unique long-distance propagation characteristic of these modes.

In most of the experimental arrangements used in this study, a compressional transducer is positioned at one end of the tube to excite a CGW mode with the coupling surface being the edge of the tube. Selection of the desirable mode is accomplished by controlling the driving frequency. Because of possible mode conversion (i.e. one mode is transformed into another) upon reflection from defects or the other tube end, it is preferrable to use such a frequency that only one mode is excitable for the given tube dimensions. In the case where we have to deal with two or more possible modes, the task of tracking the modes and interpreting the return pulses becomes quite involved, especially when the number of echoes are multiplied by the existence of several reflectors. The critical parameter that determines the possible number of modes is fd, where f is the frequency and d is the thickness of the tube wall.

In this study, we used the following types of tubing:

Thickness (mm)	Outer Diameter (mm)	Material
1.52	24.6	Inconel
1.22	18.9	Inconel
0.64	9.7	Zircaloy

Of the above tubing materials, Inconel is the material used for SGT while Zircaloy is the material of fuel rods. The results on the Zircaloy tubing are included in this report since we believe that the same results would be obtained for Inconel of equivalent dimensions. Two ultrasonic frequencies used in the experiments are 0.5 MHz and 1.0 MHz. For the considered thickness values of the tubing samples, the smallest fd value is 0.32 MHz.mm and the largest value is 1.52 MHz.mm. In this fd range, only two modes corresponding to the S_o and A_o modes of the equivalent Lamb waves are possible. In addition, when the 0.5 MHz is used, the fd value is in the lower end of this range and the A_o mode, although exists, is very weak. As a result, for 0.5 MHz the pulse train consists primarily of different reflections of the S_o mode and is therefore easier to be interpreted. In the following description of the results, the CGW pulse represents a 0.5 MHz S_o mode, unless noted otherwise.

RESULTS

Prior to investigating the interaction of a CGW mode with different types of defects, we wished to verify the fact that the CGW mode can travel along the length of a typical SGT tube. This was accomplished by sending a pulse from one end of the tube and receiving the signal at the other end. For a tube of 30 feet long, we observed that the signal is very strong and clear in comparison with the background noise. This satisfies the critical requirement that the mode must be able to propagate over such a long path in order to eliminate the need for point-by-point scanning.

EDM Notches of Different Orientation

A key concern when a CGW mode is used for inspection is the question whether one can detect cracks of different orientations with respect to the tube axis. A set of tubing samples which contain EDM notches of different orientations were fabricated for this purpose. The samples are 22" long tubes with the notches positioned at 4" from the tube end. Notches are of three types: circumferential, axial, and at a 45° angle. Figure 1a provides the dimensions of such a tubing sample with two possible transducer positions indicated. Figure 1b shows the transmitted pulse, the echo from the other tube end and a signal locating the 45° EDM notch at 18" from the transducer. The trailing edge of the EDM notch signal indicates the nature of a non-circumferential reflector. Figure 1c describes the return echo from an axial notch located at 4" from the transducer. Again, the trailing edge is quite significant in the waveform of the signal of the axial notch. Figure 1d indicates the presence of a circumferential notch at 18" from the transducer and an axial notch 4" away. It is clear that it is possible to detect cracks of all orientations, although the signal from an axial crack is weaker. One should also note that the presence of a trailing edge in the signal pulse indicates that the crack orientation is non-circumferential. The longer is the trailing edge, the more the crack orientation deviates from the circumferential direction.

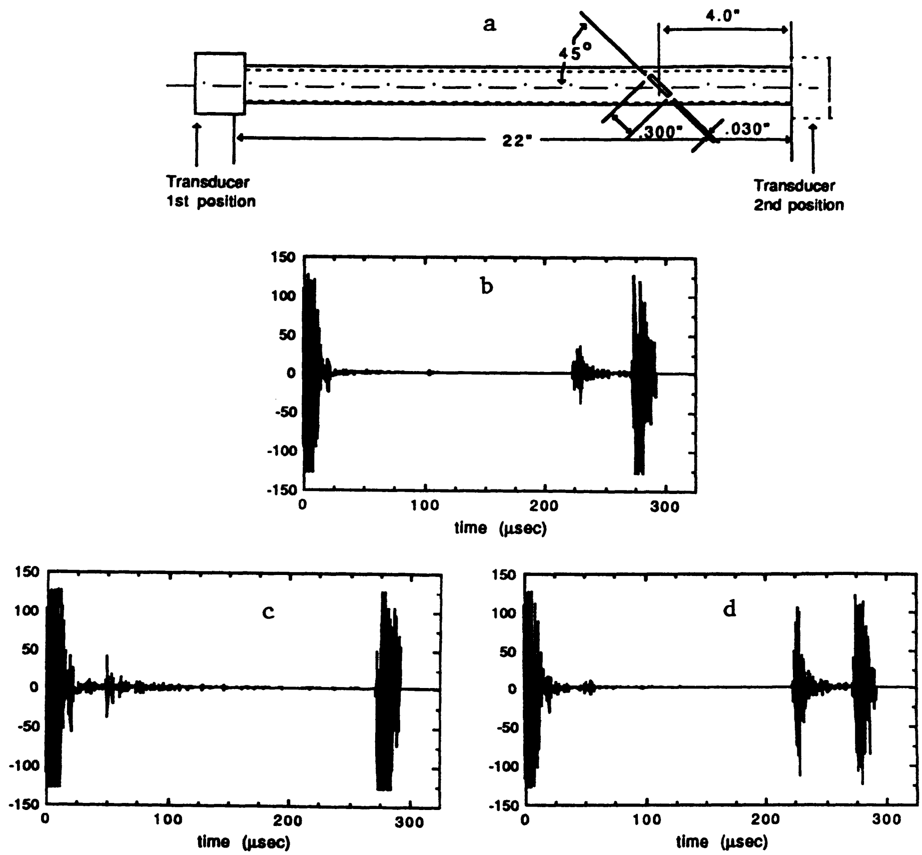

Figure 1. Inspection of EDM Notches of Different Orientations:

a. Sample Dimensions.
b. 45° Notch at 18" from Transducer.
c. Axial Notch at 4" from Transducer.
d. Axial Notch at 4" and Circumferential Notch at 18" from the Transducer.

Dependence on Notch Depth

Another question related to the problem of crack inspection is whether the CGW technique is capable of crack sizing. To address this issue, we examined the return echo from an EDM notch which was machined into the tubing sample at different depths. In a drawing Figure 2 describes the sample and notch dimensions and illustrates how the notch depth is defined. For increasing notch depths, we observed that the amplitude of the notch signal increased while the amplitude of the pulse reflected from the tube end decreased. The curve in Figure 2 summarizes these results, showing a smooth variation of the signal amplitude with the notch depth. In other words, the signal amplitude may be used to estimate the size of cracks of the same orientation. The results of the above two experiments suggest that a combination of the pulse amplitude and the extent of its trailing edge provides a means to estimate the orientation and size of a crack-like defect.

Closely-Spaced Through-Wall Holes

Another set of experiments were designed to evaluate the inspectability of a series of defects that are either closely and/or aligned in a row. Three through-wall holes of various sizes were drilled into a 22" tube. The holes were 1" apart and positioned at the far end away from the transducer. The results shown in Figure 3 demonstrate that a row of defects 1" apart should be resolvable by the CGW technique.

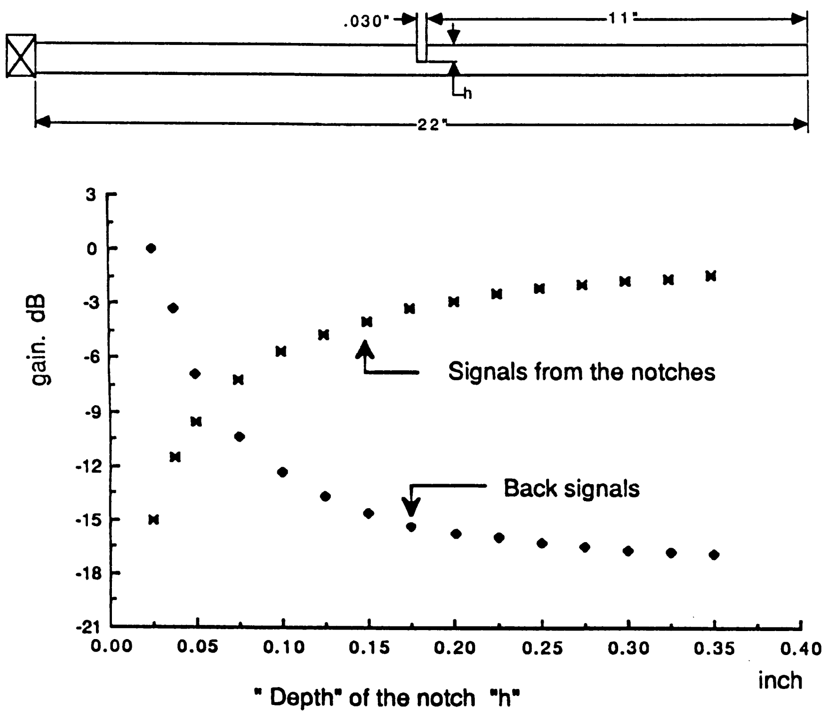

Figure 2. Dependence of Signal Amplitude on Notch Depth.

Calibration Tube

Finally, the CGW technique was tested on a calibration tube that has been used by the industry for calibration of the EC inspection systems. The tube contains 12 artificial flaws of different configurations. Figure 4 provides a drawing of the calibration tube and the test results. The rectified waveform shown in this figure indicates the presence of all known defects and demonstrates that the CGW technique should work equally well with all defect geometries considered.

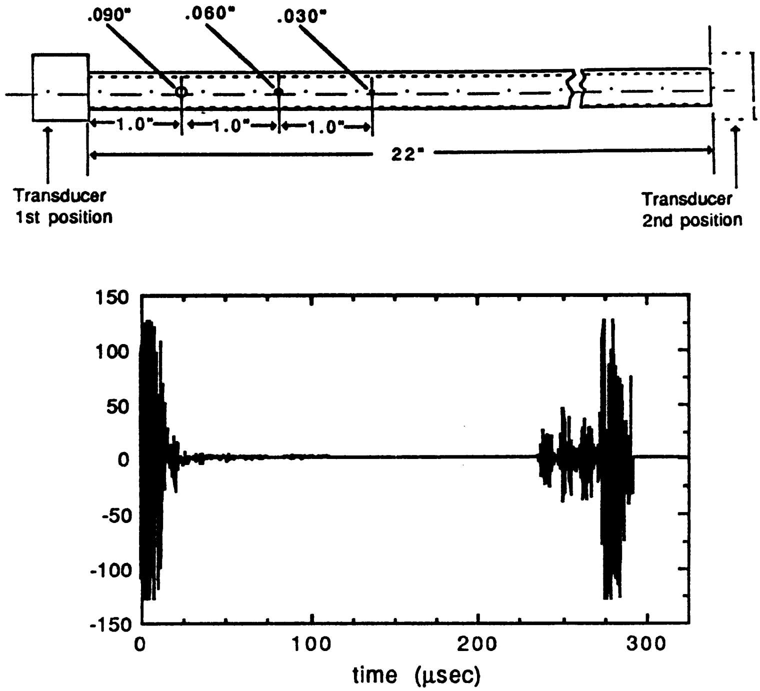

Figure 3. Inspectability of Closely Spaced Defects.

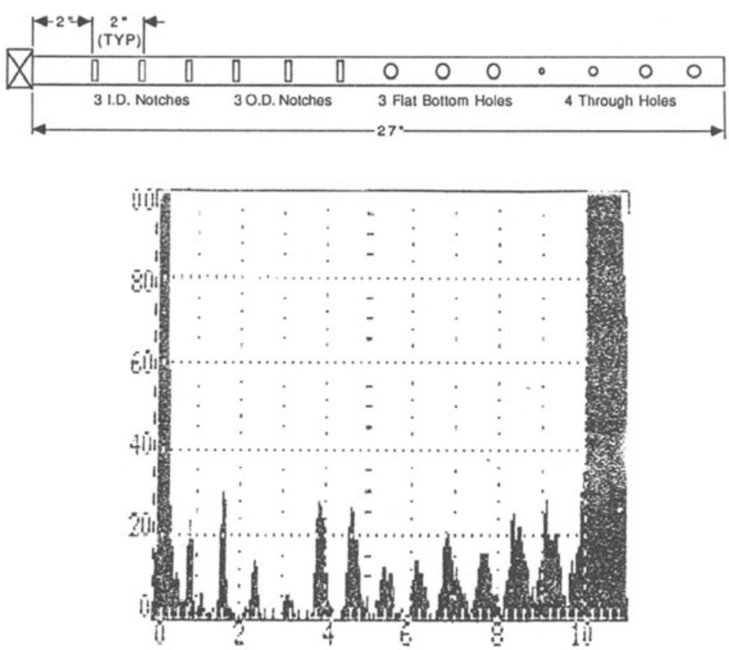

Figure 4. Demonstration of the CGW Technique on Calibration Tube.

Other Samples

The CGW technique was also demonstrated on several other samples. These include a U-bend tube section, a tube containing an actual IGSCC, and another tubing sample on which simulated corrosion-induced pitting was fabricated. Because of page limitation, these results are not included in this paper.

CONCLUSION

We have demonstrated in this paper the feasibility of using a CGW mode to inspect SGT. The proposed technique can be used for most common defect types, including axial cracks, IGSCC and corrosion-induced pitting. Defect identification is possible by the corresponding pulse shape and the signal amplitude is a good measure for sizing defects of the same type. An important finding is that mode excitability should be limited to only one mode to facilitate data interpretation.