Linear-Array Ultrasonic Waveguide Transducer for Under Sodium Viewing

Nuclear Engineering Division

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September 2010

ABSTRACT

In this report, we first present the basic design of a low-noise waveguide and its performance followed by a review of the array transducer technology. The report then presents the concept and basic designs of arrayed waveguide transducers that can apply to under-sodium viewing for in-service inspection of fast reactors. Depending on applications, the basic waveguide arrays consist of designs for sideways and downward viewing. For each viewing application, two array geometries, linear and circular, are included in design analysis. Methods to scan a 2-D target using a linear array waveguide transducer are discussed. Future plan to develop a laboratory array waveguide prototype is also presented.

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1 Introduction

Frequent inspections of reactor core structure and components are critical to the reactor safety and operation, especially for sodium-cooled fast reactors (SFRs). Liquid metals such as sodium are optically opaque; conventional optical viewing systems cannot be used for in-situ inspection. Ultrasonic techniques are commonly used for applications under liquid metals. The hostile environment of liquid sodium, high temperature and corrosiveness, poses a technical challenge to ultrasonic systems, primarily to the transducer design. Two approaches are routinely taken to meet the challenge, development of high-temperature or waveguide-based transducers. A single waveguide transducer has recently been developed at Argonne [1]. This report addresses the development of an array waveguide transducer for under-sodium viewing. The report will cover briefly the low-noise waveguide development, review the state-of-the art technologies of ultrasonic arrays, and present the waveguide arrays under development at Argonne.

2 Low-Noise Waveguide

The waveguide transducer for under-sodium imaging must function as an efficient transmitter as well as a sensitive receiver. The waveguide acts as a transmission line that isolates piezoelectric element such as PZT away from the high-temperature and corrosive environment. An ideal transmission line is the one having minimal signal attenuation, broadband sensitivity, and high signal-to-noise ratio (S/N). Hence the waveguide design must consider noise reduction, in particular, the spurious echoes from internal reflections and mode conversions. Figure 1 shows the echo signals detected by a simple smooth-rod waveguide. The echo reflected from a target is mixed in the noise, resulting in a poor S/N. To improve S/N, we have evaluated waveguides with different internal structure. Table 1 lists acoustic properties of three major waveguide designs. To enhance S/N it is more important to keep noise signals away from the target echoes. Therefore, a narrower time span of noise signals gives a better S/N, even though less energy is transmitted.

The chosen waveguide design is a combination of bundle-rod and spiraled-sheet. A prototype, shown in Figure 2, was constructed from about 35% stainless steel (SS) thin rods (0.034" in diameter) and 65% SS shim stock (0.0015" in thickness). Fabrication requires wrapping the shim stock around the inner thin rods. The waveguide ends are fill-welded by TIG or heli-arc welding and machined to flat and parallel or one end with a concave focal lens as desired.

Figure 1. Spurious noise detected by a smooth-rod waveguide

Table 1: Waveguide acoustic properties

Waveguide Design	Dimension diameter/length (inch)	% of transmitted energy into water	Waveguide attenuation (dB/m)	Time span of mode-converted signals (μ s)
Smooth Rod	0.5/6.0	6.3	0.53	30
Bundle Rod	0.5/5.5	5.08	2.59	20
Spiraled-sheet rod	0.625/5.75	1.50	1.30	3.0

Figure 2. Prototype waveguide

Performance of the prototype waveguide was tested in water. Figure 3 shows both the internal reflection and the target reflection. Both S/N and intensity of the target reflection have been significantly improved. The signal attenuation in the waveguide can be estimated from the internal reflected pulse train, shown in Figure 4, at a level of 0.8 dB/m.

Figure 3. Reflection from the tip of the prototype waveguide and a target in water

Figure 4. Reflection pulse train of 5 MHz signal propagating in the prototype waveguide

The prototype waveguide transducer has been successfully applied to under-sodium viewing. Figure 5 shows both the time-of-flight (TOF) and intensity C-scan images of the target area shown in 5(d). From these images, letters “S”, “V”, a slot with 1 mm depth and 3 mm width, a slot with 0.5 mm depth and 3 mm width, and part of a slot with 0.5 mm depth and 2 mm width are all clearly identified. These results manifest that the 12”-long prototype waveguide is able to achieve a vertical resolution of 0.5mm and a lateral resolution of 1 mm in liquid sodium when operating in 5 MHz.

(a) Acoustic Signal Reflected from Target at the Cross

(b) Time of Flight Image

(c) Intensity Image

(d) Scanning Area

Figure 5. C-scan images measured at 610°F sodium temperature

3 Linear-array Waveguide Transducers

The purpose of developing array transducers is to reduce the scan time so that the ultimate ultrasonic under-sodium viewing system can be practical, reaching the real-time inspection requirement. Ultrasonic array transducers have been developed for various applications including sonar, medical imaging and non-destructive evaluation [2-4]. To date, array transducers are constructed directly from piezoelectric elements closely spaced and arranged in various geometries depending on applications. Widely used geometries include 1-D linear array, annular array, and 2-D array. By varying the pulsing sequence, these types of array transducers, often called phase array, can electronically focus and steer ultrasonic beam to desired target area. Ultrasonic images can be synthesized by manipulating received signals from every array element. A 36 x 36 matrix-arrayed transducer has been constructed and demonstrated in sodium at 200°C (392°F) by Toshiba Corporation in Japan [4] for under-sodium viewing. The array transducer consists of 1,296 elements of PZT; each element is 2.5 mm x 2.5 mm and resonating at 5 MHz. The total size of the transducer is 190 mm x 190 mm, which can produce a 3-D image (volume image) in minutes using the synthetic aperture focusing technique. Further miniaturizing the transducer elements is needed in order to achieve the required image resolution (< 0.8 mm).

Arrayed waveguide transducer, on the other hand, has never been explored simply because miniaturization of a waveguide cannot be easily realized and it is a less effective ultrasonic transmitter because of waveguide attenuation and impedance mismatch. Furthermore, typical phase array and synthetic aperture techniques may not apply to array-waveguide transducers even though in principle steering the beam using phase-array approach is feasible. In FY 2010, we examined various 1-D linear array geometries that can achieve a line scan. Depending on the viewing sight, sideways or downward, methods to transmit signals are different. However, the basic waveguide design and array geometry are similar for both viewing applications. In general, the array consists of one transmitter and several receiving waveguides. Since it operates in pitch-catch mode, the receiving waveguides may use simple smooth rods. A reflector is needed to direct the beam. Figure 6 shows the basic design of the transmitter with a 45-degree reflector attached at end. Figure 7 shows the reflected pulses received by a 6" smooth-rod waveguide. Multiple echoes are detected along with spurious noise. A single well-defined echo but lower amplitude is detected using an 18" prototype waveguide, which is shown in Figure 7.

Figure 6. Waveguide with 45-degree reflector

Figure 7. Signal received by a smooth-rod waveguide

Figure 8. Signal received by the prototype waveguide

3.1 Linear Array for Sideway Viewing

The basic design of a linear array for sideway scan places the transmitter in the center and a number of receivers on both sides of the transmitter. The number of required receiving waveguide depends on the target length to be scanned. Figure 9 illustrates the geometry where ℓ is half of the target length and r is the distance from the target to the reflector. 45-degree reflectors are needed for both transmitting and receiving waveguides. The reflector angle (45 degree) is defined as the smaller angle between the vertical and reflecting surfaces, which makes a right-angle reflection from and to the waveguide. To scan the target, the transmitter reflector is rotated by an angle θ . At a given angle θ , the beam hits the target at a distance d from the center, given in Eq. [1]. The distances ac and ab for linear and circular array geometries, respectively, are the total beam passes, which give the corresponding time-of-flights, TOF_L and TOF_C shown in Eqs. [2] and [3].

Figure 9. Linear array geometry for sideways viewing

$$d = r \tan \theta, \quad [1]$$

$$\text{TOF}_L = 2r / (V \cos \theta), \quad [2]$$

$$\text{TOF}_C = 2r \cos \theta / V, \quad [3]$$

where V represents the sound speed in the scan medium. Figure 10 shows the calculated TOFs and the scanned target position, d , for $r = 1$ inch and $V = 0.0584$ in/ μ s (sound speed in water). The model was verified with results, shown in Figure 11, obtained from under water tests. Similar to Figure 10, Figure 12 shows the calculated results using sound velocity in 300°F sodium. It is obvious that circular geometry occupies less space than the linear array design. However, both designs can perform a linear scan from sideways direction. The imaging resolution is determined by step size of the rotating angel. To produce a 2-D image, the entire waveguide assembly translates vertically. Figure 13 shows an example of TOF changes as the array transducers scan across a target discontinuity shown in the inset (13a).

Figure 10. Time-of-flights and target locations versus rotating angles of reflector calculated in water

Figure 11. Model prediction and experimental values from in-water tests

Figure 12. Time-of-flight and target locations versus rotation angles of reflector calculated in 300°F sodium

Figure 13. Changes in time-of-flight across the target structure shown in the inset (a)

3.2 Linear Array for Downward Viewing

The downward-viewing array design differs from the sideways-viewing design in three aspects: (1) reflector angle is smaller than 45-degree and (2) transmitter is at one end of the array, and (3) only one reflector is required and it acts alone. To perform the line scan, only the vertical position of the reflector needs to be changed. For 2-D imaging additional rotation of the entire waveguide assembly is required.

Figure 14. Linear array geometry for downward viewing

Figure 14 shows the downward-viewing array geometry applied to both linear- and circular-array receivers. The initial position of the reflector, z_0 (from O to O'), and the maximum target length d_m to be scanned determine the reflector angle φ according to:

$$\varphi = \frac{1}{2} \tan^{-1} \left[\frac{d_m}{r - z_0} \right] \quad [4]$$

Once the reflector angle is defined, the target position d and time-of-flights for linear, TOF_L , and circular, TOF_C , can be determined from

$$d = (r - z) \tan(2\varphi) , \quad [5]$$

$$TOF_L = \left(z + \frac{2r - z}{\cos(2\varphi)} \right) / V , \quad [6]$$

$$TOF_C = \left(z + \frac{r \sin \beta + r - z}{\cos(2\varphi)} \right) / V , \quad [7]$$

where r is the distance from the waveguide to the target plane, z is the reflector position, and β is defined as

$$\beta = \frac{\pi}{2} - 2\phi - \sin^{-1} \left[(1 - z/r) \tan(2\varphi) \sin(2\varphi) \right] \quad [8]$$

As an example, let $z_0 = 0.1''$, $r = 1''$ and $d_m = 0.5''$, the reflector angle needs to be 14.5° . The TOFs and scanned target position, d , are calculated as functions of reflector position, z . Results are shown in Figs. 15 and 16 for the case of water and 300°F sodium, respectively.

In conclusion, we have developed arrayed waveguide transducer designs for both sideways and downward viewing. Both geometries can also be applied to 2-D imaging. Required translation stage must provide both vertical and rotational motions. Figures 17 and 18 illustrate the proposed physical designs that include the required translation stage for side view and down view geometries, respectively. In general, circular array requires less physical space but more fabrication time. Performance of both geometries will be evaluated in the future when the new translation stage is established. Required imaging software will be developed. The downward scanning geometry will initially apply to detection of the lost connecting pins used to grab the fuel assembly at Joyo test reactor.

Figure 15. Time-of-flights and scanned positions versus reflector position for the downward viewing in water

Figure 16. Time-of-flights and scanned positions versus reflector position for the downward viewing in 300°F sodium

Figure 17. Sideways scanning setup for linear array waveguide transducer

Figure 18. Downward scanning setup for linear array waveguide transducer

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