Application of Ultrasonic Guided Waves for Characterization of Defects in Pipeline of Nuclear Power Plants

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ABSTRACT

State-of-art methodologies on implementing conventional piezoelectric and flexible PVDF elements for generating ultrasonic guided waves in a tubular structure are presented. Comb transducers with PVDF can be efficiently applied to selectively excite a guided wave mode by wrapping around any size pipe while a conventional immersion type piezo-element can be also possibly used with a modification of transducer fabrication. The presented technologies can be easily applied to NDE for a large-scale tubular structure inspection.

Keywords: Axisymmetric guided waves, variable angle beam guided wave probe, comb transducer, PVDF, piping inspection.

INTRODUCTION

By virtue of the earlier pioneering investigations on guided waves[1-3], its value for various engineering application including non-destructive testing can finally draw a lot of attention these days. Pipeline inspection with guided waves is an attractive alternative to conventional bulk wave ultrasonic techniques because it is possible to inspect over long distances and underneath coatings and insulation. Increased sensitivity is also an added advantage but the optimal mode and frequency must be selected such that the wave structure in the pipe cross-section is sensitive to the defect sought in the inspection.

In addition, inspection can be complicated by the type of process fluid transported in the pipe and coatings, insulation, and water on the outer surface. As an example, an uncoated and non-insulated natural gas pipeline will typically be less difficult to inspect than a coated pipeline transporting a liquid product[4, 5].
Even though the earlier works showed a promising feasibility for the use of guided wave for piping inspections[2-5], lot of room still remains for improvement in probe design and fabrication for a better mode control. For example, the previous work for the guided wave inspection for steam generator tubings was done by an obliquely incident fixed angle beam and only the frequency sweeping was tried for a mode selection resulting in the limitation of mode control. In addition to that, a conventional piezo-ceramic element is too rigid to be properly fabricated as various shapes regardless of pipe geometry and size[5]. The flexibility problem can be overcome using PVDF film since this film can be wrapped around and mechanically coupled to the pipe. This paper also shows that mechanical coupling is an excellent alternative to the bonding steps thereby simplifying transducer construction and installation. This paper demonstrates more advanced concepts for guided wave probe design to possibly overcome the disadvantages of probe design and to a variety of probe fabrication technique for the future guided wave research.

INVESTIGATION AND COMPARISON OF GUIDED WAVE MODE CONTROLS BASED ON THE ANGLE AND ARRAY BEAM INCIDENCE

In general, it is known that there are two possible ways to design the guided wave probe for a tubular structure[1]; one is to use of angle beam incidence and the other is based on the use of array elements. Each one has its own advantage as well as disadvantage, compared to the other one. So, it can be essential to choose a right method for a guided wave fabrication, depending on the situation for inspection so that a suitable mode control and selection becomes possible with a single probe. The former way may be overall an easier and cheaper than the latter one since a single element probe with a plexi-glass wedge for a certain incident angle can generate a desired mode among the various ones that can also be excited at different angles by simply changing the angle as shown in the below.

Fig. 2 Schematic diagrams of angle beam incidence for a plate and a tubular structure and reverberation in the waveguides
However, it is not technically possible to excite a mode with the phase velocity below the wave speed in the wedge material because the Snell’s law employed for incident angle design is no longer valid in this case[2].

In addition to that, the presence of intermediate media, wedge between transducer and waveguide leads to the additional main-bang echoes and mode conversion caused by reverberation inside the wedge. More importantly, unlike the variable angle beam wedge for a plate which is placed in open space, on plate surface, it can not be easily done to design a mechanism to adjust incident angle for mode control in a limited space for a tube like heat exchanger tubing with a small diameter because it normally allows us to access only from internal surface.

The array type probe based on the use of multi-elements placed with a certain gap between two neighboring elements can be also a promising alternative to overcome those disadvantages of angle beam probe even though it could require more cost and caution in fabricating the multi-elements[3, 5, 6]. The gap of element placement is selected as a key factor for mode control and is usually set to one wavelength of a desired mode as indicated in the below. Hence, it can even generate a mode with relatively lower phase velocity. If a time delay excitation is applied, the mode control of array type probe can be also achieved even with a fixed gap[6]. The following figure also illustrates the 4-elements array type guided wave probe for piping which is placed on outer surface by clamping. In the case of a tubing inspection, flexible PVDF piezo-elements can be a robust probe material to implement the array beam guided wave probe instead of the clamping type probe due to their flexibility.

![Mode Excitation Points](image)

**Fig.3** The mode excitation points based on the use of array type probe and comb probe for piping inspection

**TRANSDUCER FABRICATION AND INSTALLATION**

1. **The Variable Angle Beam Guided Wave Probe**
Fig. 4 Installation of angle beam probe with a conical wedge and various conical wedges

Fig. 4 shows installation of angle beam probe assembly in a steam generator tube and various conical wedges for mode selection. It becomes possible to carry out mode control by the present angle beam technique varying the wedges for a desired incident angle but the reverberation in the wedges is still inevitable as the ones in plexi-glass housing of the previous work[2]. For this reason, a new concept of angle beam probe design is also proposed based on the modification of conical wedge technique. As seen in Fig. 5, conventional immersion transducers are equipped with aluminum reflectors in the new probe assembly of which heads are machined as conical surfaces corresponding to a designed reflection angle resulting in excitation of a desired mode. The gap between immersion transducer and reflector is filled with water to prevent mode conversion and minimize the internal reverberation and attenuation effects. In addition to that, employment of stiffer rubber sealant led to improvement the stability for probe centering. The probe assembly consists of transmitting and receiving units so that it allows us to investigate a further mode conversion phenomenon in a tubular structure by using the reflector of different surface angle for each one which is essential for quantification of guided wave techniques. The two units of probe assembly can be either individually or as a pair for the pulse-echo and through-transmission tests, respectively.

Fig. 5 A modified immersion type angle beam probe assembly and its reflector set: reflector surface angles (from the right) - 67°, 65°, 60°, 56.4°, 52.4°, 50°, 47°, 45°

2. The Comb Type Guided Wave Probe with PVDF elements

Comb transducers are efficient generators of axisymmetric guided waves in pipe and have many advantages compared to conventional angle beam techniques. Some of these advantages include [5,6]; uniform circumferential loading, mode and frequency tuning capability to establish natural defect wave resonances, and higher frequency excitation for improved sensitivity and resolution. The flexibility of these transducers can be limited by the rigidity of the piezocomposite[5,6]. Hence, transducer design requires element dicing and other extra manufacturing steps to fit the transducer to the pipe surface.
Presented in this section is a brief introduction of development of a comb transducer, another alternative to fabricate a guided wave probe for a tubular structure that is easy to wrap around a pipe, simple to manufacture, and simple to install. As discussed in [5,6], it can be difficult to deposit metal electrodes onto PVDF. Bonding an electrode pattern etched onto flexible polyamide to the PVDF was suggested as an alternative. The fabrication process for the pipe comb transducer used this technique but simplified the process by mechanically coupling the electrodes to the PVDF. By eliminating the bonding process, the labor associated with the adhesive application and the cost of adhesive material are eliminated. The electrodes were etched onto a polyamide backing using 4 oz. copper. An electrode width of 0.5 mm was used for both designs. The length of the electrodes is 200 mm which corresponds to the outer circumference of the pipe. Shown below is the copper finger pattern on the polyamide backing. The comb was installed by first wrapping the PVDF around the pipe followed by wrapping the electrodes over the PVDF. Pipe clamps were then installed at maximum pressure. No couplant or adhesive was used. The transducer was grounded to the pipe.

Fig. 6 A Comb type guided wave probe with PVDF elements

The design in this paper focused on exciting the $L(0,3)$ and $L(0,4)$ modes at maximum group velocity to simplify experimental verification and also because both modes have significant particle displacement at both the inner and outer surfaces, demonstrating potential for surface defect detection.

**EXPERIMENTAL SETUP, RESULTS AND DISCUSSIONS**

1. **The Variable Angle Beam Guided Wave Probe**

Figs. 7 and 8 represent the experimental setup for angle beam test and its sample result for long-range defect location.

Fig. 7 Experimental setup with the modified immersion type angle beam probe
As illustrated in Fig. 8, the modified immersion type angle beam probe provides us with a promising feature of guided wave probe enhancement with a good signal to noise ratio. The present angle beam technique can be also applied with multi probes circumferentially arranged with uniform span from each other for inspecting a pipe of larger diameter. Fig. 9 presents that the two drilled holes of 50 and 100% depths respectively can be clearly located based on this technique. Three angle beam probes of 1.0 Mhz center frequency were employed and excited in phase. This result shows a good example of the variety of guided wave probe design based on the combination of angle and array beam techniques.

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2. The Comb Type Guided Wave Probe with PVDF elements

Experiments were performed using a TISEC Structural Wave Analysis Tool (SWAT) system. The system outputs a gated sinusoid in the 50 kHz to 15 MHz frequency range at a maximum voltage of 300V. The receiver has an output level of 4V and a dynamic range of 70 dB. For both modes the frequency was swept in the vicinity of the design frequency to maximize the amplitude of the received mode. A pulse width of approximately 11.0 us was used for both modes and the receiver gain was set to 32 dB for L(0,3) and L(0,4). Group velocity measurements were in the through transmission mode at a transducer separation distance of 1800 mm. For both modes the optimal fd was found to be slightly lower than that used in the dispersion curve analysis but the group velocities compared excellently. Sample RF waveforms for both modes are provided in Fig. 10.
Fig. 10 RF waveforms of the PVDF comb array probes for L(0,3) at 2.8 MHz mm and 12 L(0,4) at 3.7 MHz mm in a 35 mm ID and 38 mm OD stainless steel pipe

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CONCLUSIONS

The modified immersion type angle beam element and flexible PVDF comb type array elements were successfully fabricated as the guided wave probes for a tubular structure inspection in this work. The design approach focused on affordability and ease of installation. It was shown that no bonding of the PVDF film to the electrodes or test structure was necessary as was done in earlier work. It turns out that the present technologies can be easily applied to NDE for a large-scale tubular structure inspection.

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