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Variable Angle Beam Guided Wave Probe Design for Tubing Based on Solid Mechanics

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Abstract A State-of-art methodologies on implementing conventional piezoelectric and flexible PVDF elements for generating ultrasonic guided waves in a tubing 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-elements can be also possibly used with a modification of transducer fabrication. Technical comparisons between the use of angle beam probe and comb one will be also discussed in detail. The presented technique can be easily applied to NDE for a long range inspection of tubular structures.

Keywords: axisymmetric guided waves, variable angle beam guided wave probe, comb transducer, piping inspection

1. Introduction

The potential of ultrasonic guided waves which can propagate along the geometry of structures was explored for the inspection of various structural integrities such as tubings, pipings and plate-like structures etc. With the use of guided waves, it has been well known that there can be many technical benefits from a nondestructive testing point of view, which involve the possibilities to inspect a large structure at some distance from a probe location without scanning the whole structure and to enhance detection sensitivity with abundance of mode selection as illustrated in Fig. 1. The benefits can allow us to develop a new state-of-art inspection way to compensate such well-known technical problems of conventional point-by-point techniques as cost and time inefficiency and limitation of accessibility under severe environments like corrosion, radiation, coating, high temperature and pressure.

The efforts for earlier guided wave researches include both theoretical and experimental works to make it possible to transfer the technology to power industry beyond the scope of pure academic subject (Viktorov, 1967, Rose et al., 1994, Monkhouse et al., 1996). In the theoretical works, the softwares for the dispersion curves and wave structures of both layered structures and cylindrical ones were developed in the aims of mode identification and determination of probe design parameters (Viktorov, 1967, Rose et al., 1994). In addition to that, the guided wave scattering simulation by boundary element method was also conducted to select best modes for detection possibility and to extract useful features for more quantitative researches for classification and sizing (Cho and Rose, 2000). Some experimental studies on the feasibility of global inspection for tubings and pipings were also presented with a variety of probe design methodologies such as angle beam incidence and comb-like array ones (Rose et al., 1994,

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Monkhouse et al., 1996, Rose et al., 1997, Quarry and Rose, 1997). The self calibration technique was used to collect and analyze guided wave data in a more reliable way regardless of the uncertainties of coupling condition, which can be applied to a quantitative guided wave inspection for power plant components.

By virtue of all those earlier pioneering investigations on guided waves(Viktorov, 1967, Rose et al., 1994, Monkhouse et al., 1996), 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.

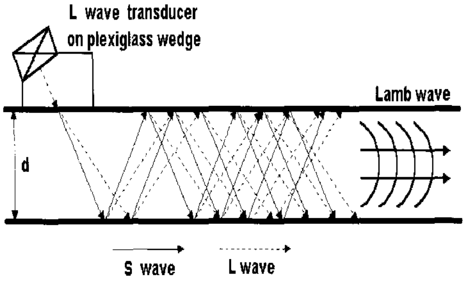


Fig. 1 A Schematic of guided wave generation with angle beam technique through wave interference on tubular structure cross-section

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(Rose et al., 1997, Quarry and Rose 1997).

Even though the earlier works showed a promising feasibility for the use of guided wave for piping inspections (Rose et al., 1994, Monkhouse et al., 1996, Rose et al., 1997, Quarry and Rose 1997), a 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(Quarry and Rose 1997). 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.

2. 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(Viktorov, 1967); one is the use of the 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 generation, 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 Fig. 2.

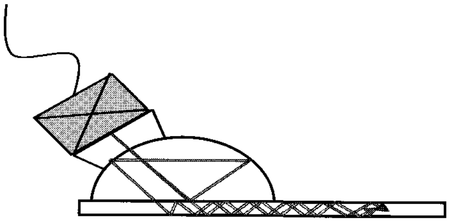


Fig. 2 A schematic diagram of angle beam incidence for a plate and a tubular structure and reverberation in the waveguides

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 (Rose et al., 1994). 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 (Monkhouse et al., 1996, Quarry and Rose, 1997, Li and Rose 2001). 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. At a given fd (frequency times thickness) value, a mode with the fixed wavelength is represented as a point on the fixed slope line corresponding to phase velocity divided by frequency as indicated(circular marks) in the left hand side figure of Fig. 3. The identical approach is applicable with the right hand side dispersion curve of Fig. 3 for a tubular structure. 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 (Li and Rose, 2001). An array type guided wave probe for pipings is placed on outer surface by clamping (Quarry and Rose, 1997). However, 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.

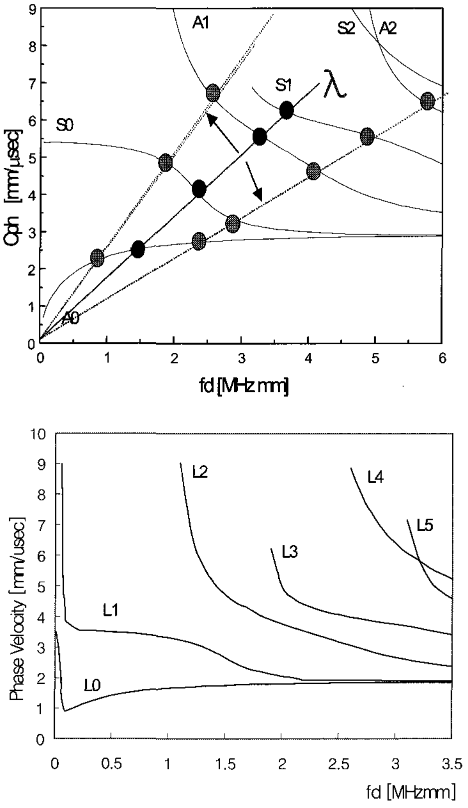


Fig. 3 The mode excitation concept based on the use of array type probe on the dispersion curve of an aluminum plate(left) and the phase velocity dispersion curve of axisymmetric modes for an inconel tube(right) (OD=22.2mm, ID=19.6mm, Cl = 5.7mm/μsec, Ct = 3.1 mm/μsec, density = 7.8 g/cm^3)

3. Transducer Fabrication and Installation

In the followings, the detailed procedures to implement the various guided wave probe fabrication concept discussed in the preceeding section will be described with emphasis on corresponding technical advantages.

3.1. Comb Type Guided Wave Probe Based on Wavelength Matching Technique

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 (Quarry and Rose, 1997, Li and Rose, 2001); uniform circumferential loading, mode and frequency tuning capability to establish natural wave resonances, and higher frequency excitation for improved sensitivity and resolution.

The flexibility of these transducers can be limited by the rigidity of the piezo composite (Quarry and Rose, 1997, Li and Rose, 2001). 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-shaped transducer with PVDF films, another alternative to fabricate a guided wave probe for a tubular structure that is easy to wrap around a pipe or tube, simple to manufacture, and simple to install. As discussed in ref. (Quarry and Rose, 1997, Li and Rose, 2001), it can be difficult to deposit metal electrodes onto PVDF. Bonding an electrode pattern etched onto flexible polyamide to the PVDF can be suggested as an alternative. The fabrication process for the pipe comb transducer also used this technique (Quarry and Rose, 1997) but the process can be simplified by mechanical coupling of 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.

As an exampole, the electrodes can be etched onto a polyamide backing using 30 m copper sheet as shown in Fig. 4. Fig. 4 also shows the copper finger pattern on the polyamide backing. The comb is 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 needs to be used while the transducer is grounded to the pipe. For detailed sample results of guided wave mode excitation with the present technique, refer to the author's earlier work (Hay et al., 2001).

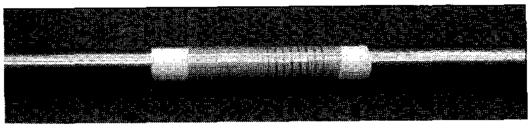


Fig. 4 A sample comb type guided wave probe with PVDF elements

3.2. The Angle Beam Guided Wave Probe

Fig. 5 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 (Rose et al., 1994). For this reason, a new concept of angle beam probe design is also proposed based on the modification of conical wedge technique.

As shown in Fig. 5, for simplicity, a conventional immersion transducers can be equipped with aluminum reflectors in the new probe assembly of which heads are machined as conical surfaces corresponding to a fixed reflection angle resulting in excitation of a desired mode. If either a tube diameter becomes smaller, let's say around 10-20 mm or a more flexible mode control is required, it will be a challenging task to design a variable angle beam probe other than a fixed angle beam one due to the limited space inside the tube although for a pipe of large diameter, the present angle beam technique illustrated in Fig 5 is still applicable. In the following, the concept for the variable angle beam probe for tubing will be discussed in details.

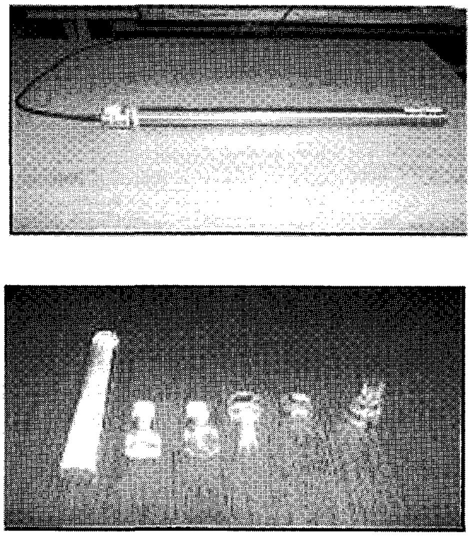


Fig. 5 Installation of angle beam probe with a conical wedge and various conical wedges

Fig. 6 represents the pictures of the probe assembly based on the modified variable angle beam technique and its replaceable reflectors set. The key idea is to combine the immersion type probe with the fixed angle beam technique introduced in the preceding paragraph. As depicted in Fig. 7, 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 phenomena in a tubular structure by using thereflector of different surface

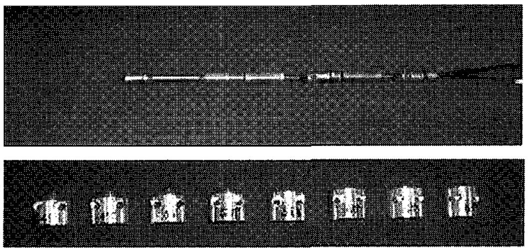
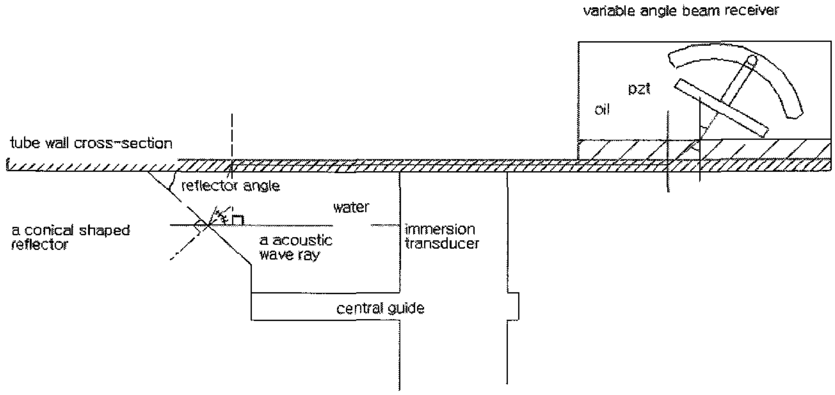


Fig. 6 A modified immersion type variable angle beam probe assembly and its reflector set : reflector surface angles (from the right) - 67。,65。,60。,56.4。,52.4。,50。,47。,45



$$\theta_{\rm II} = 45^\circ + \frac{\theta_{\rm I}}{2}$$

Fig. 7 A schematic description on reflector angle calculation and the set-up for variable angle beam probe for tubing inspection (h_I ; incident angle, h_{II} ; reflector angle)

angle for each one which is essential for quantifying guided wave techniques. The two units of probe assembly can be either individually or as a pair for the pulse-cho and through-transmission tests, respectively.

The following is a schematic of the cross-sectional probe set-up configuration for tubing experiment.

The angle of the reflector inside the variable angle beam probe assembly is defined as the half angle of a conical shaped reflector surface. Then, the incident angle for the beam entry onto the inner surface of tube is given in the simple geometrical relation seen in the above. The acoustic wave ray emanated from the immersion type transducer placed in the probe head is reflected on the conical surface of reflector so that an axisymmetric guided wave mode corresponding to the incident angle and phase velocity can be generated in the tube based on the Snell's law (Viktorov, 1967). The probe assembly is fabricated to readily replace just the conical shaped reflector for mode control while instead, the earlier design concept was to use the piezo element of a conical shaped fixed angle surface with plexiglass housing not allowing any mode control besides frequency sweeping. The frequency spectrum of the immersion transducer shows a reasonable broadband characteristic representing about 3 MHz bandwidth for 6 dB down points between 0.5 and 3.5 MHz. So, with the given thickness of inconel tube, 1.3 mm, it is assured that a proper mode frequency tuning with a consistent efficiency becomes possible over the fd(frequency*thickness) range between 0.65 and 4.55 MHz mm.

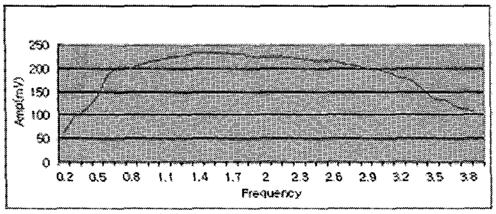


Fig. 8 A frequency spectrum of the immersion type piezo element inside the variable angle beam probe for tubing inspection

4. Experimental Setup, Results and Discussions

4.1. The Results with Fixed Angle Beam Guided Wave Probe

Figs. 9 and 10 represent the experimental setup for fixed angle beam test with the wedge technique and its sample result for long-range defect location.

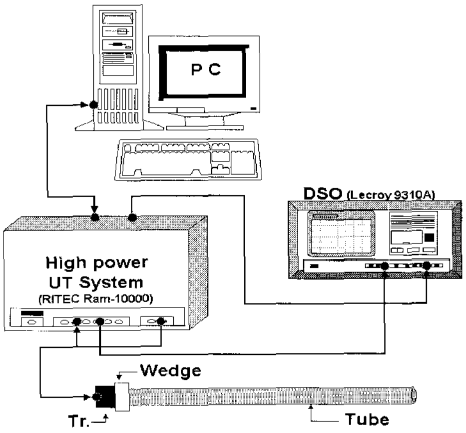


Fig. 9 Experimental setup with the fixed angle beam probe

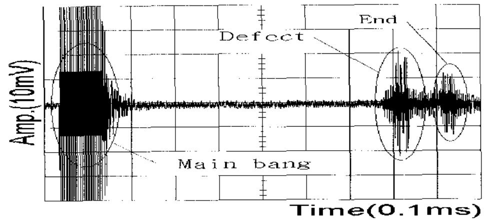


Fig. 10 Long-range defect location by the fixed angle beam technique with a 180 cm long inconel tube containing an axisymmetric circumferential defect of 10% depth to wall thickness at 200mm away from the free end

As illustrated in Fig. 10, the modified fixed angle beam probe with plexiglass wedges 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. 11 presents the guided wave reflections, the two main echoes in between the main bang and the back-wall echoes from the two drilled holes of 50 and 100 % depths and 3mm diameter, which are placed 80 and 160 cm away from pipe end, the probe location respectively in 240 cm pipe. They can be clearly located based on the array type fixed angle beam technique. Three angle beam probes with the center frequency of 1.0 MHz and the incident angle of 30 degree were circumferentially placed with 120 degree span between two neighboring elements and excited in phase. This result shows a good example of a variety of guided wave probe design based on the combination of angle and array beam techniques.

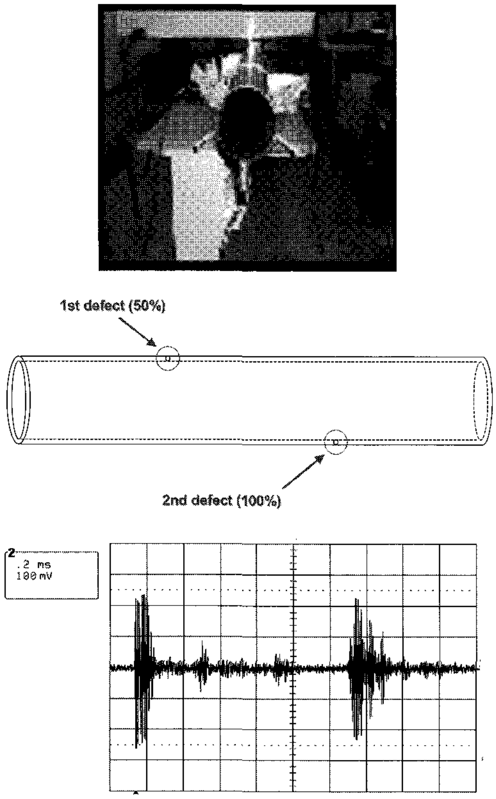


Fig. 11 Multiple defects location in a pipe with 254 mm O.D. and 5mm thickness based on the combined technique of angle and array beam incidence

4.2. The Results with Variable Angle Beam Guided Wave Probe

Fig. 12 represents the experimental setup for inconel tubing tests with the variable angle beam probe introduced in the preceding section. The tube length is 190 cm and it was vertically fixed in the frame as shown in Fig. 12 to simulate the way it is equipped inside a steam generator of nuclear power plants. The gap between a reflector and immersion type transducer is filled with water running through the central guide of the probe assembly as illustrated in Figs. 6 and 7.

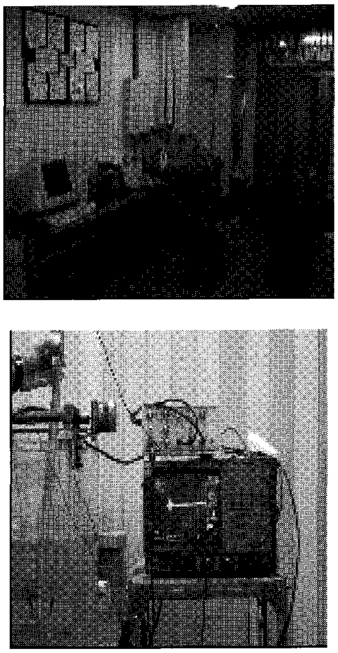
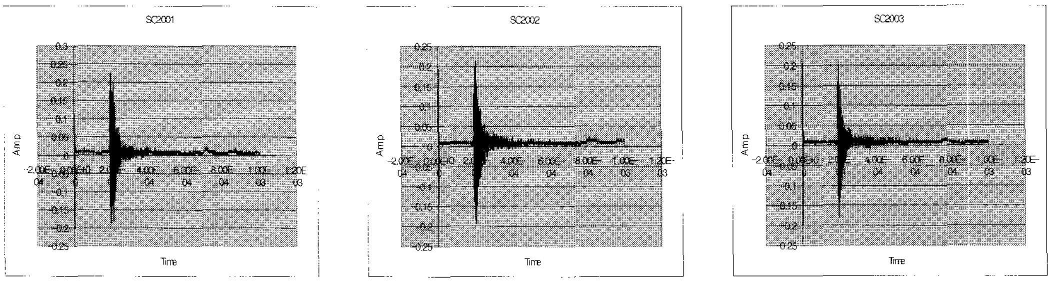


Fig. 12 Experimental setup with the variable angle beam probe

As a result of preliminary mode tuning tests, it turned out that the use of 50° reflector at 1.8 MHz provides a guided wave mode with decent signal to noise ratio. In addition, this mode was assured to be L(0,3) mode from its location on the dispersion curve of Fig. 3. A similar wave form was also obtained even with the reflectors of 56.4° and 52.4° . This could be attributed to the phase velocity and frequency bandwidth effect (Rose et al., 1994). In addition, note that there could be an inevitable gap between the data points of theoretical and experimental dispersion curves due to some difference in guessing material properties. Nevertheless, no other reflector didn't give enough efficiency in mode generation, which indicates that the present concept for reflector selection falls in a reasonable design range with the physically based dispersion curve data. For the test, the variable angle beam probe fabricated for this study was inserted and placed 10cm away from bottom end of the inconel tube of 190cm long as seen in Fig. 12. Then, generating a mode from the internally placed variable angle beam probe, the pitch-catch setup was employed by using a separate receiver, the other conventional contact type variable angle beam probe located 60cm ahead on the outer tube surface from the sender position as shown in Fig. 12. This setup allows us to gradually change receiving angle in order to instantly monitor a converted mode signal along with an incident mode when a scattered signal is obtained. In this sense, it can be also a crucial accomplishment of the present technique for a further more detailed quantitative application, compared to the earlier fixed angle beam approach confining a received mode only to the one corresponding to the fixed receiver angle.

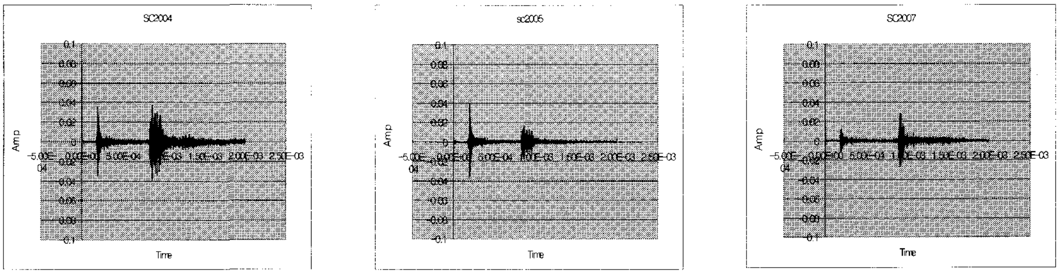
The cross-talk signal with the variable angle beam setup over 600 mm span was first obtained at 1.8 MHz, the center frequency of the variable angle beam probe to ensure signal-to-noise ratio and the axisymmetric beam profile of a guided wave mode. Fig. 13 represents the wave packet of satisfactory quality and the mode was identified again as L(0.3) from the group velocity calculation. The repeated data collection from a circumferentially different receiver position was attempted and the result indicates enhanced stability of probe placement inside a tube through the axisymmetric profile illustrated in Fig. 13 compared to the earlier work (Rose et al., 1994). The signal shape is almost identical regardless of circumferential receiver position as expected.

This is because in the present probe design, the beam transmission doesn't need to rely on the water coupling layer between internal tube surface and the plexi-glass probe housing(Rose et al., 1994) which can affect signal quality significantly. The unstability of probe placement and the subsequent lack of signal consistency are now successfully improved based on the present technique. In this case, the beam from the variable angle beam probe to internal tube surface is transmitted only through a single homogeneous bulky medium, the water reservoir filling the probe internal gap, instead of the two inhomogeneous media of the earlier work(Rose et al., 1994), the plexi-glass housing and the subsequent thin water layer. Besides the



(a) (b) (c)

Fig. 13 The cross-talk signal between the variable angle beam probe setup over 600 mm span for the inconel tube (OD=22.2mm, ID=19.6mm) at f = 1.8 MHz (X - time [sec], Y - amplitude[volt])
(a) for a receiver position at top on tube cross-section
(b) for a receiver position at 180 degree from the top on tube cross-section
(c) for a receiver position at 180 degree from the top on tube cross-section



(a) (b) (c)

Fig. 14 Sample RF waveforms of tube end reflection (the second echoes) with L(0,3) mode at 1.8 MHz
(a) a sample RF waveform of tube end reflection; (1st) the cross-talk, (2nd) tube end reflection
(b) signal damping test for the back wall-echo confirmation
(c) the end reflection variation with the receiving angle increase from 20° to 70°

versatility of convenient mode selection with a single probe assembly, the present technique also offers an excellent opportunity to simplify probe machining and assembling process resulting in a significant cost-down for guided wave probe manufacturing from a practical view point.

Following is the data on the feasibility study with the variable angle beam probe for tubing application. One of well known advantages of the guided wave technique is the possibility to apply it to a long range inspection, which demands a decent penetration performance. For this reason, the multiple reflected echoes from the tube end were carefully monitored with the 190cm long inconel tube to predict the capability of the variable angle beam probe to send a guided wave mode over a longer distance in a practical circumstance. It was successfully confirmed that the probe fabricated in this study can provide enough power to readily cover the zone over 10 m ahead with a satisfactory S/N ratio from a fixed probe position. Fig. 14 shows the gated signals of the first back-wall echo from the end of 190 cm long inconel tube. The configuration of probe setup is identical to one of the preceding tests except for the fact that the receiver is now facing to the end. Consequently, the propagation distance is set as approximately 3000 mm for this case. The experimental propagation distance through the calculation with the time of flight and the L(0,3) group velocity agrees fairly well to the real propagation distance. The first echo in RF waveforms was found to be a signal of the cross-talk between the two angle beam probes. Fig. 14 (b) and (c) represent the results of signal damping test by hand to ensure the back wall-echo and the monitoring of the end reflection variation with receiving angle increase, respectively. Compared to Fig. 14 (a), Fig. 14 (c) shows a relatively smaller cross-talk signal(1st echo) indicating the improvement in beam directivity with the receiving angle increase from 20° to 70° .

As an example of tubing inspection, the sleeving patched inconel specimens were prepared as depicted in Fig. 15.

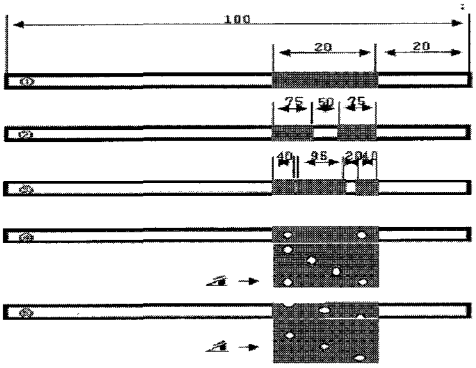


Fig. 15 The configuration for inconel tubing mock-ups patched by various external sleeving coatings ; length scale [cm]

The inspection of sleeving patched tubings is a crucial NDE issue in power industry due to the lack of efficient monitoring methodology. This is attributed to the fact that the patching process inevitably gives a sudden geometry and material property change to tubing integrities which can also lead to the occurrence of another subsequent local defects like a delamination and a lack of sleeving. So, there has been a high demand of technology development for the NDE application. In addition, the seeling patched zone is more difficult to access than other parts of tubing integrity because of the sleeving deposition demanding an alternative remote inspection scheme like the guided wave technique. In Fig. 15, the spans between neighboring deposits and artificially machined holes in sleeving zones simulate the lack or imperfection of sleeving.

Fig. 16 is the RF waveform obtained with the variable angle beam probe for the sleeving specimen #2 of Fig. 15. The multi reflections of the 2nd through 5th echoes indicate a promising feasibility to apply the present variable angle beam guided wave probe to the sleeving patched monitoring. Those three subsequent gaps between the 2nd and 5th echoes observed in time domain are matched pretty well with the corresponding spans between the sleeving ends of those two depositions located back to back. This implicates that the guided wave test with the present variable angle beam probe can also perform well to discriminate multiple defects located nearby each other with a decent axial resolution as indicated in Fig. 16. A similar results were also obtained in axisymmetric wave forms for the other two specimens #1 and #3 containing axisymmetrically defected sleeving only with different echo number and location due to the difference in sleeving profile compared to the specimen #2. As expected, the echoes associated with the specimens, #4 and #5 appeared to be no longer axisymmetric and further studies are underway to extract more detailed information on the defected sleeving profile from the echoes.

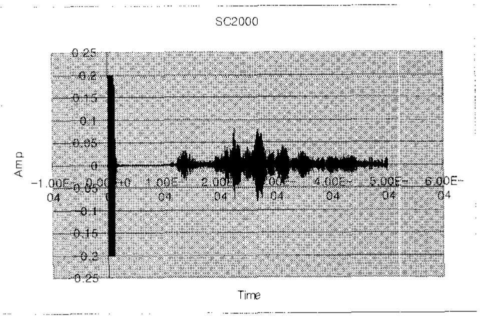


Fig. 16 The multiple reflections of L(0.3) at 1.8 mm from the two subsequent sleeving deposits of 2.5 mm with the span of 5 mm in between them.

5. Conclusions

The modified immersion type variable angle beam probe was successfully fabricated as a decent guided wave probe for a tubular structure inspection. The design approach focused on simplified probe fabrication and convenience of mode control over a conventional fixed angle beam probe. Preliminary sample test results with sleeving patched inconel tubings also show some promising feasibility for further application. It turns out that the present technologies can be efficiently applied to NDE for a long range tubular structure inspection.

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