Underwater Pipeline Inspection Using Guided Waves

Won-Bae Na

Tribikram Kundu
Fellow ASME
e-mail: tkundu@email.arizona.edu

Department of Civil Engineering and Engineering Mechanics,
The University of Arizona,
Tucson, AZ 85721

Underwater pipeline inspections are conducted using ultrasonic cylindrical guided waves in the laboratory environment. Three different types of mechanical defects—gouge, removed metal, and dent—are fabricated in small-diameter, 22.22-mm, aluminum pipes and tested. To efficiently propagate the antisymmetric (flexural) cylindrical guided waves through the aluminum pipe in water, a new transducer holder device is designed. The device uses commercially available ultrasonic transducers that generate compressional ultrasonic waves in the water. The device can change the striking angle of the incident beam from 0 to 51 deg. With the help of this device, the incident angle adjustment and frequency sweeping can be carried out. This is necessary for obtaining the time history of the received signals for various incident angles and signal frequencies; then these time histories are converted to V(f) curves, or received signal amplitude versus frequency curves. From the amplitude of these V(f) curves, the type and extent of the mechanical defects can be estimated. This investigation shows that the new coupler device can be effectively used for health monitoring of underwater pipelines using guided waves. [DOI: 10.1115/1.1466456]

Introduction

It is imperative to regularly check the integrity of pipelines since any collapse and malfunction of pipelines may cost human life. There have been several efforts to efficiently inspect the integrity of pipelines nondestructively. When inspecting pipeline in seawater, there are more challenges due to the marine environment coming from physical, chemical, and biological marine factors, which should be carefully considered in offshore pipeline inspection.

For underwater pipeline inspection, visual inspection is very old-fashioned, but still a very useful method. Other methods, such as magnetic, ultrasonic, pressure testing, and in-line service inspection, are also used for underwater pipe inspection. These methods are briefly discussed in this paper; then ultrasonic guided wave techniques employing ultrasonic guided waves are introduced as a potential method for underwater pipeline inspection.

Three different types of mechanical defects of aluminum pipes are fabricated and inspected using guided waves. Previously developed sensors and a new transducer holder are introduced for understanding transmitting and receiving mechanisms of guided waves through pipe. With these sensors, experiments are conducted and $V(f)$ curves, or received signal amplitude versus frequency curves, are obtained. Sensitivity of the $V(f)$ curves to the type and the degree of defects is studied.

In summary, the feasibility of cylindrical guided waves for detecting the mechanical defects of aluminum pipes in water is investigated in this paper.

Background

Divers and ROVs (remote operated vehicles) have been used as the principal means of underwater pipeline inspection. The inspection process includes initial visual inspection, then more detailed visual and specialized inspections, and finally, critical inspections employing an appropriate NDT (nondestructive testing) technique. The role of NDT is to discover defects that may threaten the structural integrity of pipelines such as mechanical damage, cracks, and corrosion. Serious defects are sometimes found during annual inspections of areas never before examined by NDT, and the result of these defects may be catastrophic.

The most important NDT is VI (visual inspection), which may be performed by divers and ROVs (Goldberg [1]). Although the human eye's capability of recognizing, interpreting, and analyzing is the most important tool, it needs experience. In addition, it cannot be applied for examining internal defects. MPI (magnetic particle inspection), apart from the visual examination, has been the most widely used method under water. It is a very effective method for detecting surface breaking cracks, both under and above water (Bayliss et al. [2]). In addition, the examination has to be performed by divers and areas to be examined have to be cleaned (Nordbø [3]). MFL (magnetic flux leakage) technique has similar properties as MPI and it has been used for in-line service inspection (Upda et al. [4], Mandal et al. [5]). However, MFL technique cannot detect gradual change in the wall thickness, and it cannot be used on pipes made of nonferrous materials. UI (ultrasonic inspection) is another method used for detection of subsurface defects. It is suitable for thickness measurements, weld examinations, and detection of inclusion and internal corrosion [2]. The main purpose of UI has so far been detection and mapping of internal corrosion in risers and pipelines. This UI has also been performed by divers. Other techniques are also available for underwater pipeline inspection such as acoustic emission, radiography, and eddy current [3]. These methods are at different stages of their development.

In addition to UI, the possible NDT methods for detecting the internal corrosion of underwater pipelines may be pressure testing and the use of in-line service inspection devices. Pressure testing is commonly used to verify the integrity of pipelines after installation or repairs regardless of the system's age. The pipeline is filled with water and pressurized, generally to 125 percent of operating pressure, to reveal leaks and flaws (Committee on the Safety of Marine Pipelines [6]). As a routine inspection method, pressure testing has serious limitations as follows: 1) it detects only flaws that are near critical size, and thus gives an operator little or no warning of impending failure; and 2) it requires shutting-in an entire field, and sometimes several fields. Thus, pressure testing is useful for certain purposes but not a broadly applicable means of assurance. The use of in-line service inspection (ILI) devices (more commonly referred to as smart pigs) to measure various characteristics of pipelines has continued to gain acceptance in the pipeline industry (Crump and Papenfuss [7]). A

Contributed by the Pressure Vessels and Piping Division for publication in the JOURNAL OF PRESSURE VESSEL TECHNOLOGY. Manuscript received by the PVP Division, May 16, 2001; revised manuscript received December 18, 2001. Associate Editor: J. C. Duke.

variety of ILI devices are used to provide information to pipeline operators, such as the types and locations of pipe defects, the radii and locations of bends, and even photographic images. Most of them carry instruments to measure mostly magnetic flux leakage (sometimes ultrasonic signal), which indicate metal loss. ILI devices carry their won batteries, tape recorders, and odometers. Most ILI devices in the United States has taken place in onshore pipeline systems, but the conditions of offshore pipelines are more challenging for using it. Thus, the widespread use of the devices will require substantial advances in technology. In addition, some reports mentioned that smart pig data were often hard to interpret, and in some cases erroneous [6]. Furthermore, to use the smart pigs, pipelines have to allow free passage and must have pig launch and retrieval facilities, which are not always available (Guo and Kundu [8]).

Most ultrasonic devices on smart pigs installed for thickness measurements use bulk waves. They use reflection, transmission and scattering of bulk waves by internal defects. However, such use of bulk waves for pipe wall thickness measurement is not very economic because of the inspection time. Thus, many investigators have developed guided wave techniques since these techniques have several advantages over the conventional ultrasonic methods: 1) guided waves can propagate a long distance; and 2) there are several wave modes that can have different degrees of sensitivity to different types of defects. Currently, Guo and Kundu [8,9] experimentally showed that cylindrical guided waves are sensitive to pipe defects. They developed new sensors, in the shape of a conical coupling fluid container and annular-shaped couplers, and used inclination angle and frequency sweep technique for their experiments. Many other investigators have tried to inspect for corrosion, cracks, and other types of defects in pipes by cylindrical Lamb waves (Rose et al. [10], Alleyne and Cawley [11], Chan and Cawley [12], Cheng and Cheng [13]). In these inspections, time histories recorded by the receiver have been carefully analyzed for detecting any small signal reflected by the discontinuity. Although this has been useful for detecting some defects, sometimes such small defect signals may remain undetected. Guo and Kundu [8,9] used $V(f)$ curves to detect pipe defects. However, these applications have been limited to inspection of pipelines open to air, not buried underground or immersed in water. So far, it seems difficult to find a literature reporting the application of guided waves to underwater pipeline inspection although some investigators have studied similar problems such as cylindrical guided wave leakage due to liquid loading [10]. Wang [14] reported the applications of guided wave techniques in the petrochemical industry: inspection of pipes, heater tubes, vessels, risers, and heat exchanger tubing.

In this paper, a special transducer holder used for transmitting guided waves is introduced and some mechanical defects in underwater pipe are detected from the change in the $V(f)$ curve. Ideally, the inclination angle and sweeping frequency should be controlled to launch the cylindrical guided mode (or cylindrical Lamb mode) that is most sensitive to the pipe damage and least prone to attenuation. We have designed and fabricated a new transducer holder for efficiently generating cylindrical guided waves in underwater pipes. This new design is described in this paper and some experimental results generated by the new device are also reported.

Figure 1 shows two coupler mechanisms used for the pipe inspection. For the design in Fig. 1(*a*), plexiglas is used as a couplant. The plexiglas has annular shape with cylindrical and conical inner walls and spherical outer wall. The pipe fits inside the cylindrical inner hole of the annular shape. The transducers can be mounted on the spherical outer surface, and hence, one or more transducers can be placed on the spherical surface. Striking angle can be changed simply by sliding the transducers on the spherical outer surface [9]. The maximum range of transmitter angle is 51 deg for this arrangement. For underwater inspection, the new coupler as shown in Fig. 1(*b*) is introduced. In this design the plexiglas is removed from the design of Fig. 1(*a*) and water is used as a couplant instead of plexiglas and Vaseline. This type of water coupling should be most effective for underwater pipe inspection. The maximum range of transmitter angle is 51 deg for this case also.

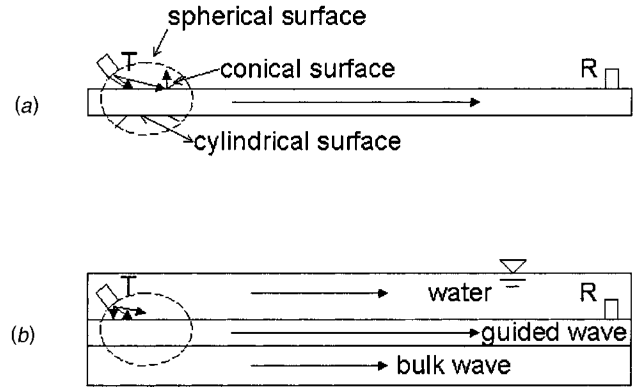

Fig. 1 Two types of transducer holders used in this research—(*a*) annular plexiglas holder, and (*b*) annular holder without plexiglas

Experimental Setup

Five different aluminum pipes containing three different types of defects were inspected. The outer and inner diameters of the pipes are 22.22 mm and 19.05 mm, respectively, and the pipes are 610 mm long. The defects are removed metal, dent, and gouge, as shown in Fig. 2. Most mechanical damage discontinuities are combinations of these primary types of anomalies (Davis and Budenik [15]). Definition of these anomalies are given in [8] as follows: 1) dent is a localized depression or deformation in the pipe's cylindrical geometry resulting from an applied force; 2) gouge is a forceful movement of metal in a local area on the surface of a pipe resulting in wall thinning and cold working of the pipe wall; and 3) removed metal is the removal of metal from the pipe surface by an applied force.

Figure 2 shows the defect free pipe and four pipes containing gouge, dent, and removed metal-type defects. Two different dimensions of removed metal-type defects were used and denoted by the term removed metal (less) and removed metal (more) in Fig. 2. The detail description of fabricating process is given in [8].

A laboratory made ultrasonic unit was used for generating the signals. Broadband parametric transducers were excited using a MATEC 310 gated amplifier by tone burst signals from a WAVETEK 395 function generator. Here, the central frequency of the transducers is 500 kHz. The signal after being propagated through the pipe wall was received by a receiver and was amplified by a MATEC 605 gated amplifier. This signal was digitized by the gage 40 MHz data acquisition board, and then the digitized received signal was displayed on a computer monitor as a function of time (time history curves). A time window (or gate) was placed to capture the initial part of the time history curves to compute the average amplitude of the signal within the given time window. The signal frequency was varied from a minimum to a maximum value. The variation of the average signal amplitude against frequency is called the $V(f)$ curve, i.e., the received signal amplitude versus the frequency curve. To get smooth $V(f)$ curves, the following parameters were adjusted by the computer system: position and width of the time window, starting frequency, frequency step size, and final frequency. Figure 3 shows the experimental setup. Here, the transmitter is held by the newly designed ellipsoidal shaped transmitter holder that is shown in Fig. 1(*f*). The receiver was located on the aluminum pipe and wooden supports were used to support the pipe. The distance between the transmitter and receiver was 500 mm.

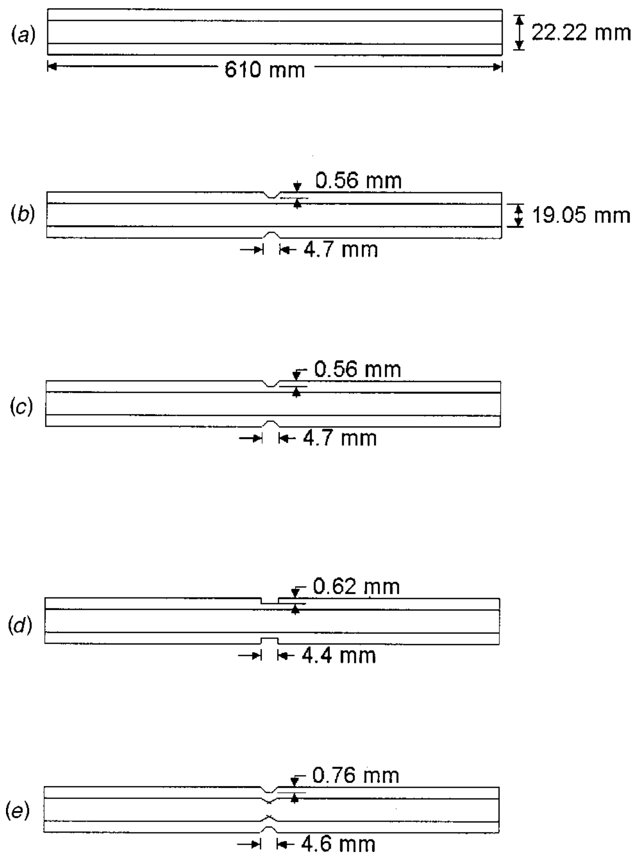

Fig. 2 Aluminum pipe specimen—(*a*) defect free; (*b*) gouge; (*c*) removed metal (less); (*d*) removed metal (more); and (*e*) dent. All pipes have same length, outer radius, and inner radius.

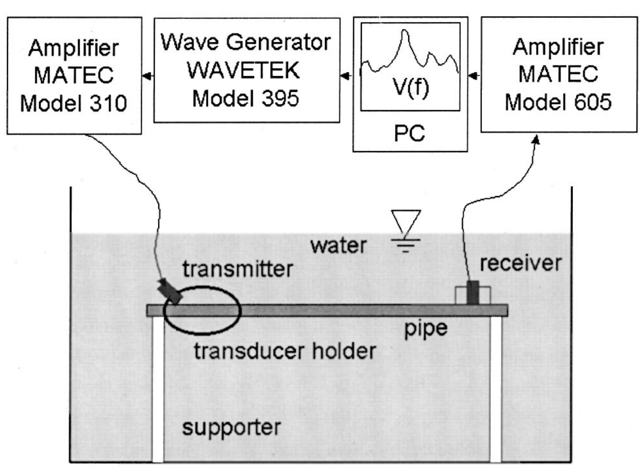

Fig. 3 Schematic of experimental setup

Experimental Results

All experiments were carried out seven times to investigate the consistency of the experimental results and then these values are averaged. Each test was conducted at different circumferential locations. Figure 4 gives the $V(f)$ curves of the pipe with dent for different incident angles, varying from 0 to 51 deg. The angle is measured relative to a plane normal to the pipe axis. Figure 4(*a*) shows the $V(f)$ curves when the transmitter-receiver arrangement of Fig. 1(*a*) was used and Fig. 4(*b*) shows the $V(f)$ curves when the transmitter-receiver arrangement of Fig. 1(*b*) was used. In Fig. 4(*a*) and 4(*b*), the strongest signals are obtained for transducer incident angles of 20 and 51 deg, respectively.

For the experimental setup of Fig. 1(*a*), 20 deg incident angle was selected since it gives the strongest signals and for the experimental setup of Fig. 1(*b*), 51 deg striking angle was selected for the same reason. Since only one transmitter is used to generate guided waves, nonaxisymmetric cylindrical guided waves are generated during experiments. If we use a larger number (four or more) of transducers uniformly placed around the pipe and then excite them in the same phase, we generate strong axisymmetric modes and weak nonaxisymmetric modes [9].

Figure 5 shows the average values of $V(f)$ curves for five different pipe specimens that have: (a) no defect, (b) gouge, (c) remove metal less, (d) remove metal more, and (e) dent as shown in Fig. 2. For these curves, the transmitter-receiver arrangement is shown in Fig. 1(*a*) and the transmitter angle is 20 deg. From the figure, it is not very clear that the guided wave technique can detect and distinguish different types and degree of mechanical defects, although there are some trends at peak positions.

Figure 6 shows the average values of $V(f)$ curves for the same five pipe specimens studied in Fig. 5. However this time, the transmitter-receiver arrangement as shown in Fig. 1(*b*) is used. The transmitter angle is 51 deg. From the figure, it is clear that the

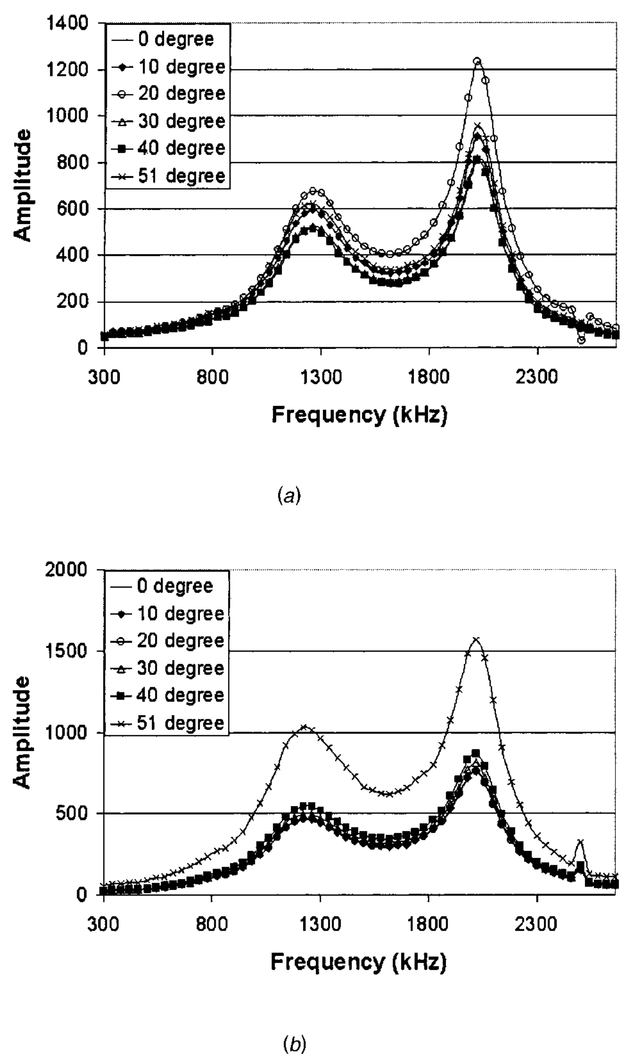

Fig. 4 $V(f)$ curves of the aluminum pipe with dent for different incident angles using transmitter-receiver arrangement, as shown in (*a*) Fig. 1(*a*), and (*b*) Fig. 1(*b*)

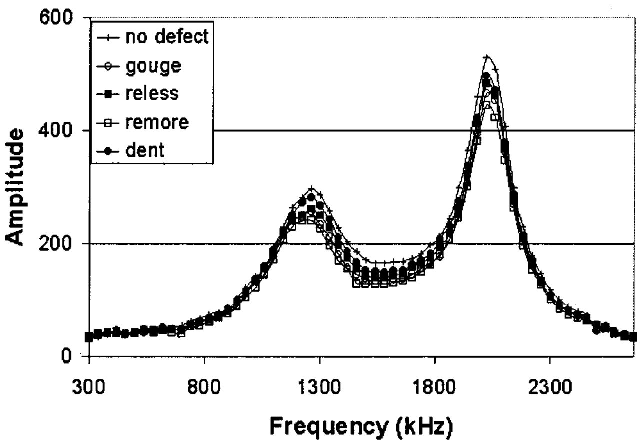

Fig. 5 The average values of $V(f)$ curves of aluminum pipes for 20 deg transmitter angle for five different defects using transmitter receiver arrangement, as shown in Fig. 1(*a*)

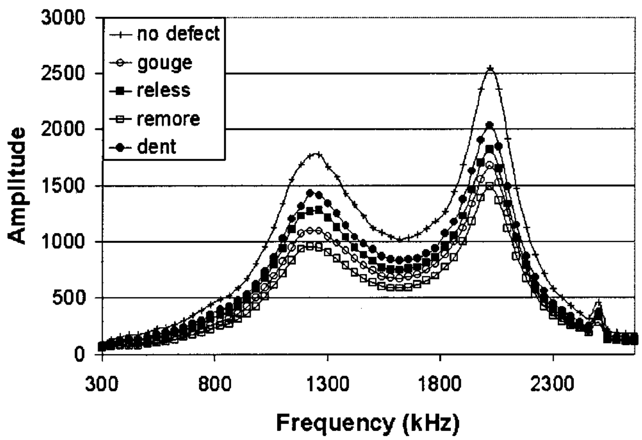

Fig. 6 The average values of $V(f)$ curves of aluminum pipes for 51 deg transmitter angle for five different defects using transmitter receiver arrangement, as shown in Fig. 1(*b*)

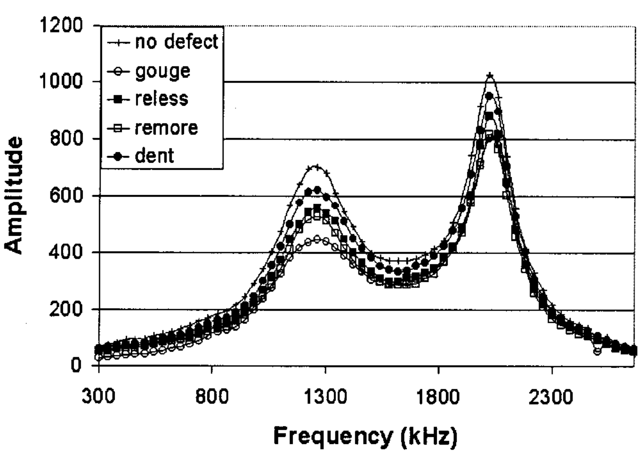

Fig. 7 The average values of V(f) curves of aluminum pipes for 51 deg transmitter angle for five different defects using transmitter receiver arrangement, as shown in Fig. 1(*a*)

guided wave technique can clearly distinguish between different types of mechanical defects. Defect discrimination in Fig. 6 is much more than that in Fig. 5.

Figure 7 shows the average values of $V(f)$ curves for the same five pipe specimens. The transmitter-receiver arrangement for this case is shown in Fig. 1(*a*) and the transmitter angle is 51 deg. In this case also $V(f)$ curves show sensitivity to defect types. However, for this case, the difference between $V(f)$ curves for gouge and remove metal more is not very clear at the second peak position and the $V(f)$ curves corresponding to these two defects at the first peak position is different from that of Fig. 5.

From these experimental results it is concluded that 51 deg transmitter angle gives good results for both transmitter-receiver arrangements as shown in Figs. 1(*a*) and 1(*b*). Between these two the arrangement in Fig. 1(*b*) appears to be the better arrangement. It should be noted here that the two peaks at 1.26 and 2.02 MHz in the $V(f)$ curves correspond to two cylindrical guided wave modes.

Analytical Study

To identify the wave modes corresponding to the two peaks in the $V(f)$ curves, the phase velocity dispersion curves are obtained. Cylindrical guided waves are dispersive and the dispersive pattern is complex. For drawing the dispersion curves, the material properties of the specimen structure must be known. In this case, the specimen is an aluminum pipe surrounded by water or vacuum. When the surrounding medium is vacuum, the pipe walls are traction-free and the computation of dispersion curves is not very difficult. However, the computation becomes more complex when the surrounding medium is water. In addition, many wave modes appear close to one another for aluminum pipes surrounded by water; then it is not easy to identify which modes correspond to the peaks in the $V(f)$ curves.

The material properties of aluminum pipes are as follows: 1) density=2.7 g/cm^3, 2) longitudinal wave speed=6.32 km/s, and 3) shear wave speed=3.13 km/s. These values are obtained from material handbook and the attenuations of aluminum pipes are ignored. To plot the peaks of the $V(f)$ curves on the dispersion curves, Snell's law is used as follows:

$$V_{\mathrm{ph}}=\frac{V_c}{\mathrm{Sin}\,\theta} \tag{1}$$

where, V_{ph} is the phase velocity of the cylindrical guided wave in the pipe, V_c is the longitudinal wave speed in the coupling medium between the transducer and the pipe (for plexiglas $V_c = 2.77$ km/s; for water $V_c = 1.48$ km/s), and θ is transmitter angle. From Snell's law we can calculate the phase velocity of cylindrical guided waves. For plexiglas coupling, the calculated phase velocities are 3.56 and 8.10 km/s for 51 and 20 deg transmitter angles, respectively. For water coupling, the calculated phase velocity is 1.90 km/s for 51 deg transmitter angle. As discussed in the previous section, the frequencies corresponding to the two peaks are 1.26 and 2.02 MHz, respectively.

Only 1st, 2nd, and 3rd flexural wave modes of the pipe in vacuum are shown in Fig. 8 since only one transmitter is used on one side of the pipe during the experiments. Hence, strong non-axisymmetric (flexural) modes in the pipe wall will be generated for this transmitter arrangement. The 4th and higher-order modes are not plotted since those modes are not very strong for our transmitter-receiver arrangement. For comparison purposes longitudinal wave modes are also plotted in Fig. 8.

In Fig. 8, the solid squares show the experimental points (frequency=1.26 MHz, phase velocity=3.56 km/s and frequency =2.02 MHz, phase velocity=3.56 km/s), when 51 deg transmitter angle is used and the solid circles show the experimental points (frequency=1.26 MHz, phase velocity=8.10 km/s and frequency =2.02 MHz, phase velocity=8.10 km/s), when 20 deg angle is used. Note that the phase velocities 3.56 km/sec and 8.10 km/s are obtained from Eq. (1) by substituting θ=51 and 20 deg, respec-

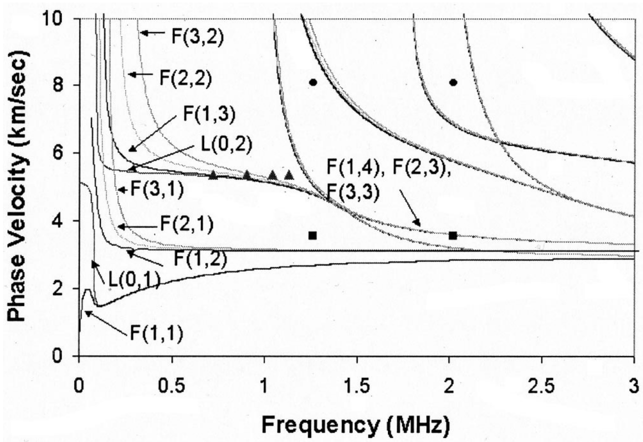

Fig. 8 Phase velocity dispersion curves of the aluminum pipe in vacuum. Longitudinal, 1st, 2nd, and 3rd flexural wave modes are shown. Solid squares and circles correspond to the peak positions of the $V(f)$ curves for 51 and 20 deg transmitter angles, respectively. Solid triangles correspond to peak positions of the $V(f)$ curves for 31 deg transmitter angle [9].

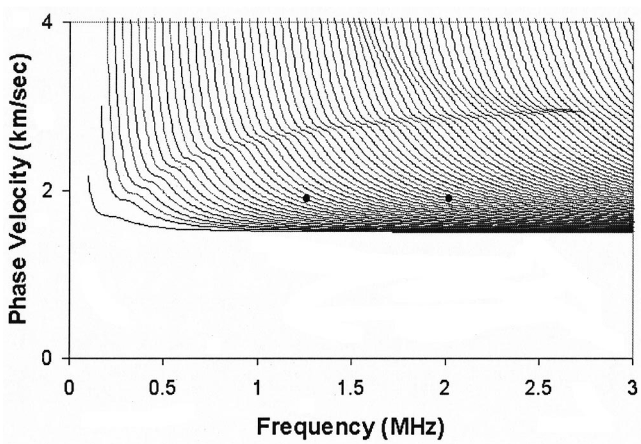

Fig. 9 Phase velocity dispersion curves of the aluminum pipe in water. Longitudinal and 1st flexural wave modes are shown. Solid circles correspond to the peak positions of the $V(f)$ curves for 51 deg transmitter angle.

tively. The positions of solid squares are near the asymptote of some flexural wave modes. Since the 51 deg transmitter angle gives better results than 20 deg angle for this set of specimen we can conclude that the wave modes near the asymptote of flexural wave modes are more efficient for this inspection. Guo and Kundu [9] and Ghosh et al. [16] observed similar phenomenon for pipes and plates as well. Guo and Kundu [9] used 31 deg incident angle for their tests. Their peaks are plotted in Fig. 8 with solid triangle symbols. These points are also near the asymptote of some flexural wave modes.

Longitudinal and 1st flexural wave modes of the pipe in water are shown in Fig. 9. The second and higher flexural modes are not shown because even without those modes too many curves appear in Fig. 9.

Two solid squares of Fig. 9 show the experimental points, (1.26 MHz, 1.90 km/s) and (2.02 MHz, 1.90 km/s), when 51 deg transmitter angle is used. In Fig. 9, the corresponding wave modes cannot be clearly identified since there are too many wave modes in the neighborhood of the experimental points. In addition, if the higher-order flexural wave modes (2nd and 3rd) are plotted then more dispersion curves appear. However, in spite of all those uncertainties one can say that the positions of solid squares are near the asymptote of flexural wave modes. Hence, for modes to be sensitive to the defect type those must be close to the asymptotes of flexural modes.

Summary and Conclusion

To investigate the feasibility of flexural cylindrical guided waves for inspecting the mechanical defects of underwater pipes, a new coupler mechanism is designed. Incident angle adjustment and frequency sweep technique are used to generate, propagate, and receive the guided waves through the pipes in water. This study shows that the new coupler is an efficient device and the guided wave inspection technique is an effective tool for health monitoring of underwater pipelines. An analytical study is carried out to identify the cylindrical guided wave modes that are sensitive to the mechanical defects. Dispersion curves of aluminum pipe in air and water are shown. Dispersion curves for aluminum pipes surrounded by water show too many modes. From the analytical study, it is shown that flexural cylindrical guided wave modes near asymptotes of the dispersion curves are more sensitive to the defects in comparison to the modes that are not close to the asymptotes.

This study shows the feasibility of using ultrasonic guided waves for underwater pipeline inspection. The new transducer holder and its coupling mechanism have potential to be used for underwater pipe inspection.

Acknowledgments

This research was financially supported by the NSF grant CMS-9901221 and the EPRI Grant EP-P241/C110.

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