**[Original paper]**
*Journal of the Korean Society*
*for Nondestructive Testing*
*Vol. 31, No. 3 (2011. 6)*

# Damage Detection in Lab-Scaled Underwater PVC Pipes Using Cylindrical Lamb Waves

Dongwoo Woo* and Won-Bae Na*†

**Abstract** This study presents a nondestructive test for underwater PVC pipes. To use guided ultrasonic waves, specially denoted by cylindrical Lamb waves, a test setup was made in a water tank using the pitch and catch mode and specimens were made to give artificial cutouts located in the circumferential direction of the pipes. Total three states of damaged levels were considered to see how the guided waves interact with the defects. For the experimental adjustments, three different pipe diameters (60, 90, 114 mm) were tested, and two factors - incident angle (10 and 40°) and distance (50 and 200 mm) - were tried. From the results, regardless of the diameters and two experimental factors, it is shown that the degrees of defects were recognized through amplitude and arrived time of the very first part of the received cylindrical Lamb waves. Between amplitude and arrived time, it is found that the amplitude gives more sensitive results.

**Keywords:** Damage Detection, Underwater Pipes, PVC, Cylindrical Lamb Waves

## 1. Introduction

Pipelines installed in oceans need a regular safety assurance to primarily prevent environmental damages or pollution caused by their failures. The typical pipeline failures come from corrosion and mechanical damages usually happened to the outside wall surface of marine pipelines[1]. These damages or corrosion may cause the leakage; hence, very often the leakage invokes marine environmental issues, power plant shutdown, etc, which make loss of industrial products and social instability[2]. History has verified how leakage of crude oil in a way of oil spill is critical as shown in Exxon Valdez Oil Spill (1989), Hebei Spirit Oil Spill (2007), and recent Louisiana Oil Spill (2010). Therefore, oil pipelines should be carefully checked to assure their safety, otherwise a catastrophic environmental problem may occur.

There are several ways to check the heath of marine pipelines. Those ways can be classified into three categories: by divers and ROVs (remotely operated vehicles), pressure test with 120% operating pressure, and in-line service inspection using smart pigs. Each way has its own advantages and disadvantages[3,4]. However, the first method has been widely used for its simplicity and economical benefit. The other two methods accompany a partial and whole shutdown of pipelines; hence, a well-operated approach or strategy is required. Recently, to overcome the existing problems in the typical inspection or testing methods, guided ultrasonic waves-based approach has been tested. Many investigators showed that guided ultrasonic wave or cylindrical Lamb waves can be effective and efficient for underwater pipeline inspection; however, the verification is still under construction[5,6]. Therefore, this study

---

[Received: April 18, 2011, Revised: May 27, 2011, Accepted: June 3, 2011] *Department of Ocean Engineering Pukyong National University Busan 608-737, Republic of Korea, †Corresponding Author: wna@pknu.ac.kr

focuses on how cylindrical Lamb waves can be useful for mechanically fabricated damage detection for underwater PVC pipelines. For the goal, PVC pipes were tested, three different damage levels were simulated and incident angles and distances were adjusted.

## 2. Cylindrical Lamb Wave

The wave propagation in cylindrical structures such as rods and pipes is analogous to that in plates. The SH and symmetric modes of plate have their analogous in torsional and longitudinal wave modes, while the anti-symmetric plate modes are analogous to the flexural modes of cylinders. It is known to be possible to consider each type of motion separately and derive frequency equations to torsional, longitudinal, and flexural modes. However, it is also possible to develop a general frequency equation for the problem and then to resolve it into various modes, done by Gazis in the analysis of hollow cylinders[7,8]. Meeker and Meitzer[9], following the approach of Gazis, developed the Pochhammer-Chree equations for a solid cylinder this manner. Detail information on this technique can be found in the references[10-15].

More difficult problem is the problem of leaky guided waves in cylinders. For solving this problem, many works have been performed by several investigators[16-22]. For a three-layered cylinder, the schematic diagram is shown in Fig. 1. In the figure, layers 1 and 2 represent finite layers and layer 3 represents infinite space surrounding the cylinder. The partial waves (L+-, SV+-, SH+-) combine to form a guide wave and the cylindrical system is axi-symmetric and infinitely long. The detailed explanation of so-called 'global matrix method' for solving the problem can be found in many literatures[23-26]; hence, we skip the procedure.

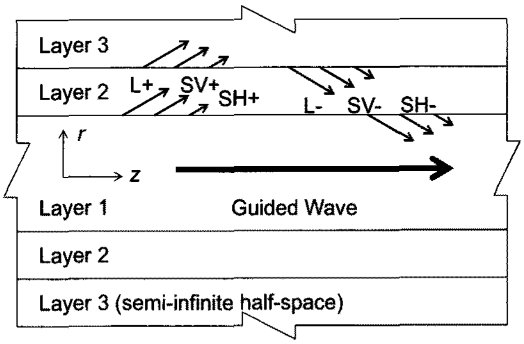


Fig. 1 Schematic diagram for three-layered cylinder

Following Silk and Bainton[27], the following three notations are used for categorizing the infinite numbers of cylindrical guided wave modes: (1) L(0,*m*), longitudinal axially symmetric modes; (2) T(0,*m*), torsional axially symmetric modes; and (3) F(*n*,*m*), axially non-symmetric (flexural) modes. The first index, *n*, denotes the circumferential order of the mode, which means the integer number of wavelengths around the circumference of the cylinder. The second index, *m*, describes a counter variable. In the case of both symmetric cases, the first index is zero. For example, L(0,1) is the first longitudinal wave mode of circumferential order 0. The first longitudinal guided wave mode L(0,1) is called the fundamental longitudinal wave mode.

## 3. Materials and Method

The goal of this study is characterizing how cylindrical Lamb waves propagate through underwater pipelines and investigating if the waves can detect mechanically fabricated artificial defects. For the goal we made an experimental setup shown in Fig. 2 and we fabricated mechanically damaged defects as shown in Fig. 3. Table 1 summarizes the properties of used PVC pipes. As shown in Fig. 2, two immersion transducers were used for the test as a transmitter and receiver. The central frequency of the transducers is 1 MHz. The pulse-receiver was used for the pitch and catch method, and data acquisition was made by an oscilloscope and a PC. As shown in Fig. 3, the types of defects are defect free, half defect, and full defect. Here, half defect means that the defect depth is the half of the pipe wall thickness and full defect indicates that the defect depth is the same as the pipe wall thickness. The defect length is 40% of the circumferential length of the pipe. As experimental factors, we selected incident angle and incident distance to investigate how those factors affect experimental results. Those are 10 and 40° for the angle and 50 and 200 mm for the distance. These two angles are selected after calculating the critical angle for longitudinal and shear wave propagation, by using Snell's law.

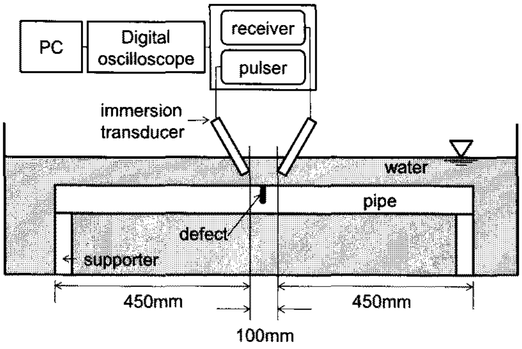
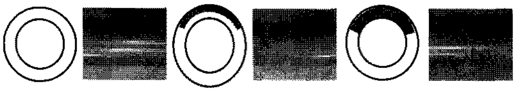


Fig. 2 Schematic diagram of experimental setup



(a) no defect (b) defect with half cut (c) defect with full cut

Fig. 3 Mechanically fabricated defects

Table 1 Properties of PVC pipes

| Material | Outside diameter [mm] | Wall thickness [mm] | Length [mm] |
|---|---|---|---|
| PVC | 60 | 4.5 | 1000 |
|  | 90 | 5.9 | 1000 |
|  | 114 | 7.1 | 1000 |

## 4. Experimental Results

Fig. 4 shows the received signals obtained from the 60 mm-diameter PVC pipes without any defect (defect free). The incident distance is fixed to 50 mm but the incident angles are 10° and 40°, respectively. The figure shows that the received signal in the case of 10° angle has more wave modes than that of 40° incident angle. However, it shows arrived time from 40° angle is faster than that of 10° angle. Fig. 5 also shows the received signals obtained from the 60 mm-diameter PVC pipes. However, the incident distance is fixed to 200 mm for the figure. The figure shows similar results to Fig. 4. Although the signals obtained from 90mm and 114 mm-diameter PVC pipes are not shown here, we found the signals give similar results with the 60 mm. Therefore, we select incident angle and distance as experimental factors to investigate how those factors affect damage detection.

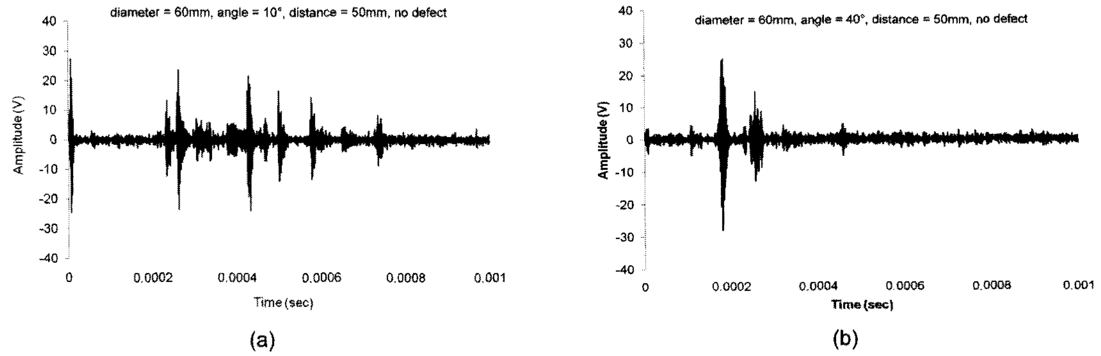


Fig. 4 Received signals in the cases of (a) incident angle 10° and (b) incident angle 40° when the incident distance is 50 mm, outside diameter is 60 mm, and PVC pipe is defect free

Because of the complexity of the received signals, the very first part of the received signals is investigated for all of the cases. Tables 2, 3 and 4 show the amplitudes and arrived times of the first received signals through 60 mm, 90 mm and 114 mm-diameter, respectively. As shown in the tables, in some cases for the PVC pipes with full cut defect, we could not acquire the received signals. These no-signal-acquires are all happened in the cases of 10° incident angle for 60 mm and 114 mm-diameter PVC pipes. To visualize those tables, Figs. 6 to 11 show the amplitudes and arrived time of received signals, respectively. In general, it is found from the figures, as defect increases, the amplitude decreases and arrived time becomes slower. By comparing amplitude with arrived time, we can see the amplitude change gives more sensitive result than arrived time, which means the degrees of defects are easily captured through the amplitude change. This result is very similar with the results

Table 2 Amplitude and arrived time of the first received signals traveled through 60 mm-diameter PVC pipe

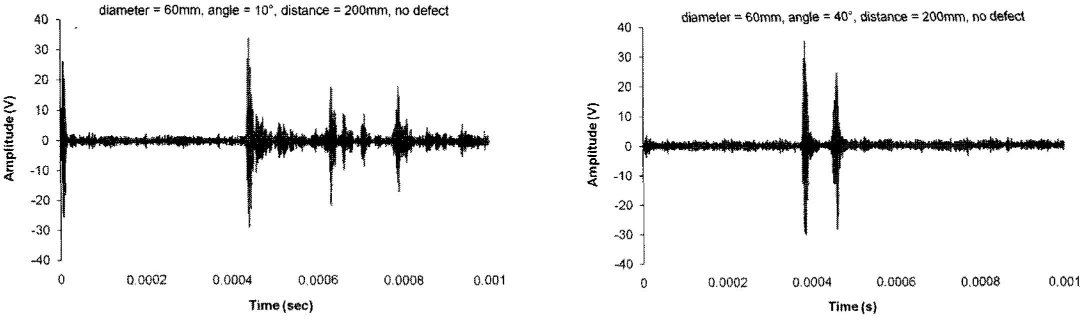
| Inc. angle (°) | Distance (mm) | Damage | Amplitude (V) | Time (μsec) |
|---|---|---|---|---|
| 10 | 50 | No defect | 13.41 | 230 |
| | | Half cut | 7.78 | 237 |
| | | Full cut | No signal | No signal |
| | 200 | No defect | 34.00 | 433 |
| | | Half cut | 27.07 | 433 |
| | | Full cut | No signal | No signal |
| 40 | 50 | No defect | 24.91 | 169 |
| | | Half cut | 21.41 | 169 |
| | | Full cut | 16.53 | 173 |
| | 200 | No defect | 35.12 | 376 |
| | | Half cut | 28.66 | 376 |
| | | Full cut | 24.61 | 380 |

Table 3 Amplitude and arrived time of the first received signals traveled through 90 mm-diameter PVC pipe

| Inc. angle (°) | Distance (mm) | Damage | Amplitude (V) | Time (μsec) |
|---|---|---|---|---|
| 10 | 50 | No defect | 14.40 | 194 |
| | | Half cut | 10.51 | 194 |
| | | Full cut | 5.54 | 196 |
| | 200 | No defect | 30.92 | 398 |
| | | Half cut | 26.29 | 398 |
| | | Full cut | 21.55 | 398 |
| 40 | 50 | No defect | 23.11 | 204 |
| | | Half cut | 16.80 | 206 |
| | | Full cut | 15.55 | 207 |
| | 200 | No defect | 28.67 | 410 |
| | | Half cut | 19.19 | 410 |
| | | Full cut | 17.78 | 414 |

Table 4 Amplitude and arrived time of the first received signals traveled through 114 mm-diameter PVC pipe

| Inc. angle (°) | Distance (mm) | Damage | Amplitude (V) | Time (μsec) |
|---|---|---|---|---|
| 10 | 50 | No defect | 10.41 | 224 |
| | | Half cut | 436 | 226 |
| | | Full cut | No signal | No signal |
| | 200 | No defect | 34.58 | 424 |
| | | Half cut | 26.58 | 428 |
| | | Full cut | No signal | No signal |
| 40 | 50 | No defect | 18.67 | 245 |
| | | Half cut | 10.84 | 246 |
| | | Full cut | 8.19 | 250 |
| | 200 | No defect | 15.17 | 443 |
| | | Half cut | 5.65 | 444 |
| | | Full cut | 5.48 | 451 |



(a) (b)

Fig. 5 Received signals in the cases of (a) incident angle 10° and (b) incident angle 40° when the incident distance is 200 mm, outside diameter is 60 mm, and PVC pipe is defect free

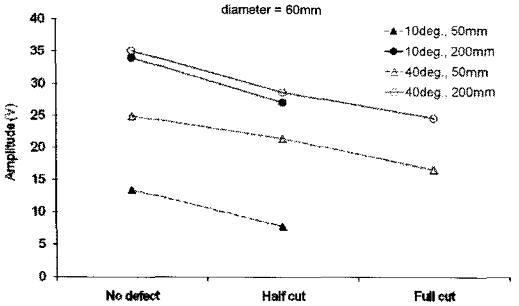


Fig. 6 Amplitude of the first received signals in the cases of 60 mm-diameter PVC pipes

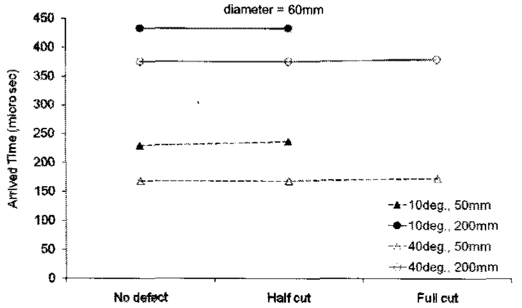


Fig. 7 Arrived time of the first received signals in the cases of 60 mm-diameter PVC pipes

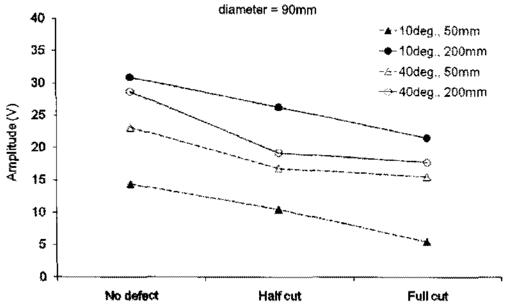


Fig. 8 Amplitude of the first received signals in the cases of 90 mm-diameter PVC pipes

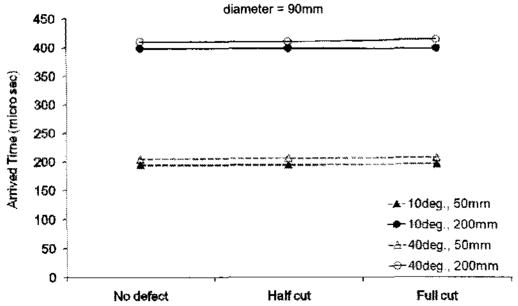


Fig. 9 Arrived time of the first received signals in the cases of 90 mm-diameter PVC pipes

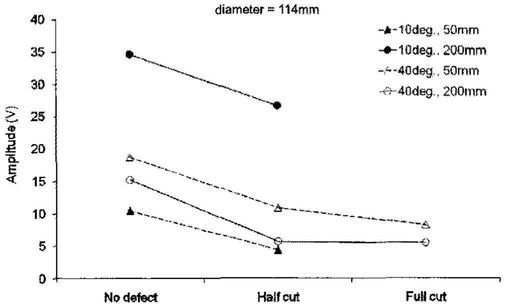


Fig. 10 Amplitude of the first received signals in the cases of 114 mm-diameter PVC pipes

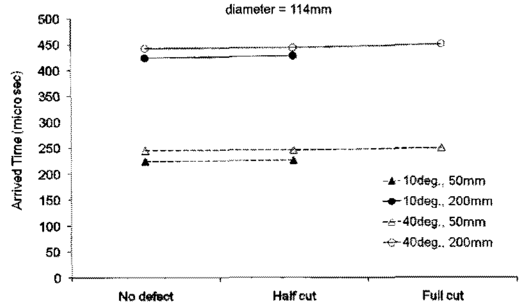


Fig. 11 Arrived time of the first received signals in the cases of 114 mm-diameter PVC pipes

obtained from the previous tests[5] for underwater steel pipes; hence, the test setup and method extend the feasibility of cylindrical guided waves.

## 5. Summary and Conclusion

This study presents a nondestructive test for underwater PVC pipes. The test tool is guided ultrasonic waves, specially denoted by cylindrical Lamb waves. Test setup is made in a water tank using the pitch and catch mode and specimens are made to give artificial cutouts located in the circumferential direction of the PVC pipes. Total three states of damaged levels are considered to see how the guided waves interact with the defects. For the experimental adjustments or test verification, three different pipe diameters (60, 90, 114 mm) are tested, and two factors - incident angle (10 and 40°) and distance (50 and 200 mm) - are tried. From the experimental results, regardless of the diameters and two experimental factors, it is shown that the degrees of defects are well recognized through amplitude and arrived time of the very first part of the received cylindrical Lamb waves. Between amplitude and arrived time, it is found that the amplitude gives more sensitive result than arrived time. This result is very similar with the results obtained from the previous tests for underwater steel pipes; hence, the test setup and method extend the feasibility of cylindrical guided waves. More pipe material types such as cast iron will be tested to verify how the waves catch the degrees of defects as a future study. In addition, for field application, this study should be extended to larger pipe diameters. This concern is another issue for a future study.

## Acknowledgement

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund) (KRE-2008-331-D00589).

## References

[1] K. A. Macdonald, A. Cosham, C. R. Alexander and P. Hopkins, "Assessing mechanical damage in offshore pipelines-two case studies," *Engineering Failure Analysis*, Vol. 14, pp. 1667-1679 (2007)

[2] S. W. Tien, W. T. Hwang and C. H. Tsai, "Study of a risk-based piping inspection guideline system," *ISA Transactions*, Vol. 46, pp. 119-126 (2007)

[3] N. B. S. Gloria, M. C. L. Areiza, I. V. J. Miranda and J. M. A. Rebello, "Development of magnetic sensor for detection and sizing of internal pipeline corrosion defects," *NDT&E International*, Vol. 42, pp. 669-677 (2009)

[4] Committee on the Safety of Marine Pipelines Improving the Safety of Marine Pipelines, National Research Council, National Academic Press, Washing DC (1994)

[5] D. Woo and W. B. Na, "Mechanically Fabricated Defects Detection on Underwater Steel Pipes using Ultrasonic Guided Waves," *Journal of Ocean Engineering and Technology*, Vol. 24, No. 1, pp. 140-145 (2010)

[6] W. B. Na and T. Kundu, "Underwater pipeline inspection using guided waves," *Transactions of ASME Journal of Pressure Vessel Technology*, Vol. 124, pp. 196-200 (2002)

[7] D. C. Gazis, "Three dimensional investigation of the propagation of waves in hollow circular cylinders," *Journal of the Acoustical Society of America*, Vol. 31, pp. 568-572 (1959)

[8] D. C. Gazis, "Three dimensional investigation of the propagation of waves

in hollow circular cylinders ii numerical results," *Journal of the Acoustical Society of America*, Vol. 31, pp. 573-572 (1959)

[9] T. R. Meeker and A. H. Meitzler, "Guided wave propagation in elongated cylinders and plates," Eds. W. P. Mason and R. N. Thurston, *Physical Acoustic Principles and Methods*, Vol. 1A, pp. 111-167, New York, Academic Press (1972)

[10] J. D. Achenbach, "Wave Propagation in Elastic Solids," North-Holland (1984)

[11] K. F. Graff, "Wave Motion in Elastic Solids," Dover (1991)

[12] H. Kolsky, "Stress Waves in Solids," Dover (1963)

[13] P. K. Meitzler, "Backward-wave transmission of stress pulses in elastic cylinders and plates," *Journal of the Acoustical Society of America*, Vol. 38, pp. 835-842 (1965)

[14] M. Onoe, H. D. McNiven and R. D. Mindlin, "Dispersion of Axially Symmetric Waves in Elastic Solids," *Journal of Applied Mechanics*, Vol. 29, pp. 729-734 (1962)

[15] J. L. Rose, "Ultrasonic Waves in Solid Media," Cambridge University Press (1999)

[16] R. Kumar, "Flexural vibrations of fluid-filled circular cylindrical shells," *Acustica*, Vol. 24, pp. 137-146 (1971)

[17] P. B. Nagy, "Longitudinal guided wave propagation in a transversely isotropic rod immersed in fluid," *Journal of the Acoustical Society of America*, Vol. 98, pp. 454-457 (1995)

[18] J. L. Rose, Y. Cho and J. J. Ditri, "Cylindrical guided wave leakage due to liquid loading," Eds. D. O. Thompson and D. E. Chimenti, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 13, pp. 259-266, Plenum Press, New York (1994)

[19] J. A. Simmons, E. Drescher-Krasicka, and H. N. G. Wadley, "Leaky axisymmetric modes in infinite clad rods," *Journal of the Acoustical Society of America*, Vol. 92, pp. 1061-1090 (1992)

[20] M. Vines, Y. Tshukahara, C. K. Jen and J. D. N. Cheeke, "Leaky Torsional Modes in Infinite Clad Rods," Journal of the Acoustical Society of America, Vol. 95, pp. 701-707 (1994)

[21] B. N. Pavlakovic, M. J. S. Lowe, D. N. Alleyne and P. Cawley, "Disperse: A general purpose program for creating dispersion curves," Eds. D. O. Thompson and D. E. Chimenti, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 18, pp. 239-246, Plenum Press, New York (1997)

[22] B. Pavlakovic and M. Lowe, "Disperse: User's Manual Version 2.0.11," Imperial College, University of London, Non-Destructive Testing Laboratory (2001)

[23] L. Knopoff, "A matrix method for elastic wave problems," *Bulletin of Seismological Society of America*, Vol. 54, pp. 431-438 (1964)

[24] M. J. Randall, "Fast programs for half-space problems," *Bulletin of the Seismological Society of America*, Vol. 57, pp. 1299-1315 (1967)

[25] H. Schmidt and F. B. Jensen, "A full wave solution for propagation in multilayered viscoelastic media with applications to Gaussian beam reflection at liquid-solid interfaces," *Journal of the Acoustical Society of America*, Vol. 77, pp. 813-825 (1985)

[26] A. Mal, "Wave propagation in layered composite laminates under periodic surface loads," *Wave Motion*, Vol. 10, pp. 257-266 (1988)

[27] M. G. Silk and K. F. Bainton, "The propagation in metal tubing of ultrasonic wave mode equivalent to Lamb waves," *Ultrasonics*, Vol. 17, pp. 11-19 (1979)