Long-Range Guided Wave Inspection of Structures Using the Magnetostrictive Sensor

Hegeon Kwun*, Sang-Young Kim*, and Glenn M. Light*

Abstract Long-range guided wave inspection is a new emerging technology for rapidly and globally inspecting a large area of a structure from a single test location. This paper describes a general overview of the guided wave properties and its application for long-range inspection of structures, the principle and instrument system for a guided wave inspection technology called "magnetostrictive sensor (MsS)" that generates and detects guided waves electromagnetically in the material under testing, and examples of long-range guided wave inspection of structures that can be accomplished using the MsS.

Keywords: guided wave, long-range inspection, magnetostrictive sensor (MsS), pipe, tube, plate

1. INTRODUCTION

1.1 Guided Waves and Their Properties

Guided waves refer to mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bounded medium (such as pipe, plate, rod, etc.) parallel to the plane of its boundary. The wave is termed "guided" because it travels along the medium guided by the geometric boundaries of the medium.

Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave [1,2]. In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of the guided waves varies significantly with the wave frequency and the geometry of the medium. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders.

To illustrate the properties of guided waves, examples of their dispersion curves (which refer to the relationship between the velocity and the wave frequency) are given in Figures 1 and 2 for pipe and plate geometries, respectively. In pipe, the guided waves exist in three different wave modes: longitudinal (L), torsional (T), and flexural (F). In plate, they exist in two different wave modes: longitudinal that is generally called "Lamb" waves and exists in symmetric (S) and antisymmetric (A) modes, and shear horizontal (SH).

1.2 Long-Range Inspection

Although the properties of guided waves are complex, with judicious selection and proper control of wave mode and frequency, the guided waves in relatively low frequencies (up to a few hundred kHz) are excellent for globally inspecting a large area of a structure from a single sensor location.

The long-range guided wave inspection involves: (1) installing a guided wave probe or sensor on the structure under inspection, (2) generating a short pulse of guided waves in the structure, and (3) detecting waves that are reflected from defects in the structure as the generated guided waves propagate along the length of the structure. As an example, the long-range guided wave inspection of pipe from outside is schematically described in Figure 3. From the occurrence time of the defect signal and the signal amplitude, the axial location and severity of the defect are determined.

Applied Physics Division, Department of NDE Science and Technology, Southwest Research Institute, San Antonio, Texas, 78238 U.S.A.

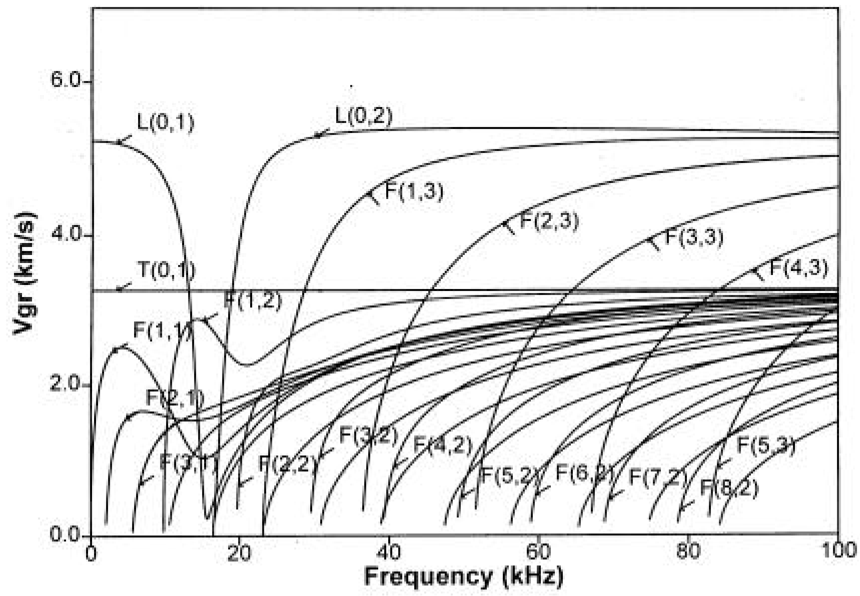


Figure 1. Examples of dispersion waves of various guided wave modes in pipe (for 4.5-inch-OD, 0.338-inch-thick pipe). The numbers in parenthesis indicate the order of the wave mode.

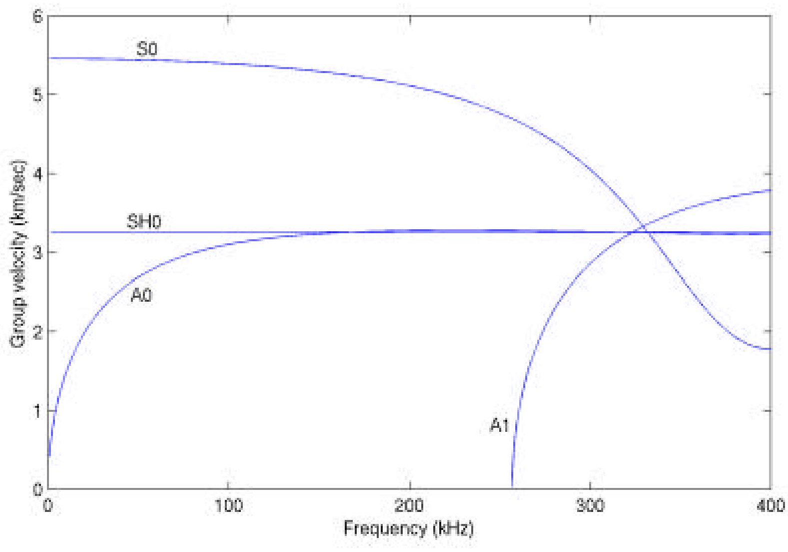


Figure 2. Example of dispersion curves of various guided wave modes in plate (for 0.25-inch-thick plate). The numbers after the letter (0 and 1) indicate the order of the wave mode.

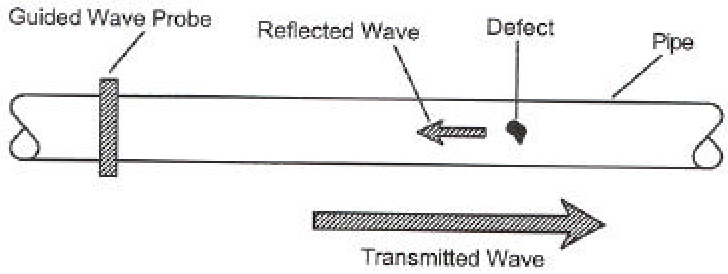


Figure 3. Guided wave inspection of piping

Guided waves illuminate the whole crosssection of structure and, therefore, can detect any surface, near-surface, and internal defects. Low-frequency guided waves have low wave attenuation (at 100 kHz, typically no more than approximately 0.1 dB/ft in bare pipe and approximately 0.3 dB/ft in bare plate; plate has a higher wave attenuation because of the beam spreading that is absent in pipe) and, therefore, can propagate a long distance along the structure. Consequently, a 100-percent volumetric inspection of a long segment of structure can be quickly and economically achieved by using the low-frequency guided waves.

The typically achievable inspection range is more than 100 feet in bare pipe and more than 30 feet in bare plate. When the structure is coated with materials such as bitumen or polyethylene, buried in the ground, or embedded in concrete, the wave attenuation is greater and the achievable inspection range is shorter.

For long-range inspection, the cross-sectional area of detectable defect size in pipes is typically 5 percent of the total pipe-wall crosssection or larger. In plates, it is typically 10 percent of the guided wave beam size.

The long-range guided wave inspection is very useful for quickly surveying a large area of structure for defect areas that may be further examined in detail using conventional inspection techniques. The long-range guided wave inspection is particularly useful for inspecting areas that are difficult to access from a remotely accessible location such as insulated pipelines, pipelines at high elevations, buried pipelines, pipelines at road crossings, tubes in heat exchangers, steel cables in highway bridges, and nuclear containment liners under concrete floors.

2. TECHNICAL BACKGROUND ON THE MAGNETOSTRICTIVE SENSOR (MsS) TECHNOLOGY

2.1 Sensor Principle

The MsS technology, developed and patented by SwRI [3], uses a probe that generates and detects guided waves electromagnetically in the material under testing. For wave generation, it relies on the magnetostrictive (or Joule) effect that refers to a small change in the physical dimensions of ferromagnetic materials – on the order of several parts per million in carbon steel – caused by externally applied magnetic field. For wave detection, it relies on the inverse-magnetostrictive (or Villari) effect that refers to a change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain). Since the probe relies on the magnetostrictive effects, it is called "magnetostrictive sensor (MsS)."

2.2 Sensor Configurations and Instrumentation

A schematic diagram of the MsS and associated instruments for generation and detection of guided waves is illustrated in Figure 4. The sensor is configured to apply a time-varying magnetic field to the material under testing and to pick up magnetic induction changes in the material caused by the guided wave. For cylindrical objects (such as rod, tube, or pipe), the MsS is ring-shaped and consists of a coil that encircles the object, as schematically drawn in Figure 5. For plate-like objects, the MsS is rectangular-shaped and consists of a coil wound on a U-shaped core, as schematically drawn in Figure 6.

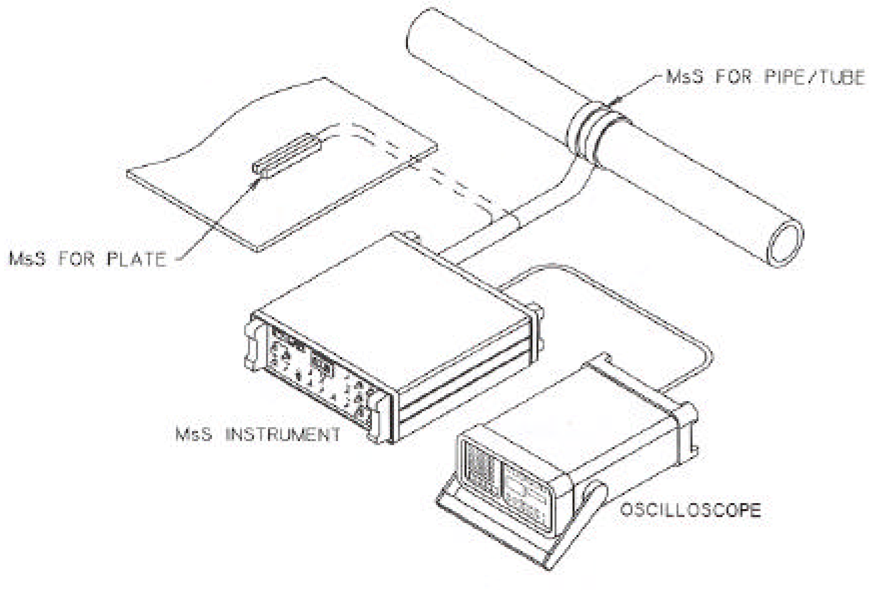


Figure 4. A schematic diagram of the MsS and associated instruments for generation and detection of guided waves

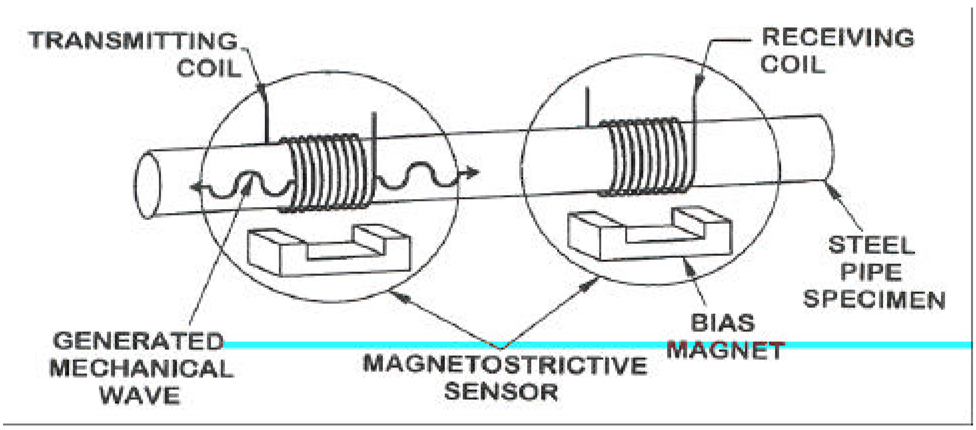


Figure 5. Schematic diagram of MsS probe for guided wave generation and detection in pipe

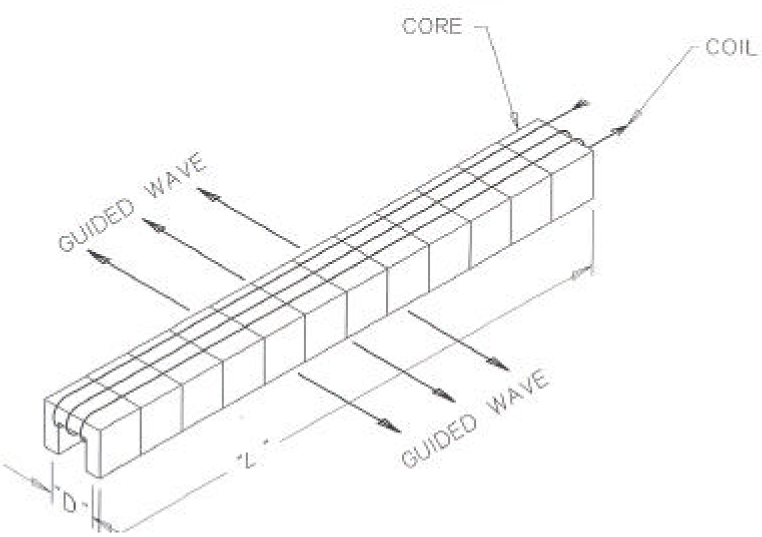


Figure 6. Schematic diagram of MsS probe for guided-wave generation and detection in plate

The MsS instrument (Models MsSR-1000 and 1010) is composed of a transmitter section and receiver section. The MsS instrument contains two transmitters and two receivers to allow the directionality control of the generated and detected guided wave signals so that the data analysis can be facilitated,. The output signals of the receiver section are displayed on a digital oscilloscope or on a PC equipped with an A/D card.

For guided wave generation, a short pulse of electric current is supplied to the transmitting MsS coil. The time varying magnetic field produced by the transmitting coil expands and contracts the material underneath the sensor via the magnetostrictive effect, thus generating the guided waves in the material. Detection of guided waves is achieved by the reverse process, where the guided waves arriving at the sensor location cause the magnetic induction of the material underneath the sensor to change with time. The changing magnetic induction, in turn, induces in the receiving MsS coil an electric voltage, which is detected.

For operation, the MsS requires that the ferromagnetic material under testing be in a magnetized state. This is achieved by applying a DC bias magnetic field to the material using either a permanent magnet (illustrated in Figure 5), electromagnet, or residual magnetization induced in the material. The DC bias magnetization is necessary to enhance the transduction efficiency of the sensor (from electrical to mechanical and vice versa) and to make the frequencies of the electrical signals and guided waves the same.

2.3 Technical Features

Technical features of the MsS include the following:

- Electromagnetic guided wave generation and detection -- No couplant required and capable of operating with a substantial gap to the material surface (up to a few inches on pipe and up to approximately 0.25-inch on plate).
- Good sensitivity in frequencies up to a few hundred kHz -- Ideal for long-range guided wave inspection applications.
- Easy wave mode control.

The operating guided wave modes of the MsS are:

- Longitudinal (L) and torsional (T) wave modes in cylindrical objects.
- Lamb and shear horizontal (SH) wave modes in plates.

The operating wave mode of the MsS is controlled by the relative alignment between the DC bias magnetic field and the time-varying magnetic field produced by the MsS. For L wave modes in cylindrical objects and Lamb wave modes in plates, a parallel alignment is used. For T wave modes in cylindrical objects and SH wave modes in plates, a perpendicular alignment is used. The guided waves propagate in the direction parallel to the direction of the time-varying magnetic field produced by the MsS.

The MsS is directly operable on structures made of ferrous materials such as carbon steel or alloyed steel [4-9]. The MsS is also operable on structures made of non-ferrous materials, such as aluminum, by using a thin layer of ferromagnetic material placed under the MsS. In the latter case, the guided waves are generated in the ferromagnetic layer and coupled to the non-ferrous structure. Detection is achieved through the reverse process.

3. EXAMPLES OF LONG-RANGE INSPECTION

3.1 Cylindrical Structures

3.1.1 Inspection of Water-Filled Pipeline

Figure 7 shows example data that were obtained using a 35-kHz T mode guided wave from a 168-foot-long, 4.5-inch-OD, 0.337-inch-wall carbon steel pipeline that was filled with water. The configuration of the pipeline is illustrated on the top of the figure. It consisted of three 42-foot-long pipe joints that were welded together and flanged at both ends. It also contained various simulated corrosion defects, notches, and holes. Symbols used to indicate the geometric features and simulated defects are as follows: Wi – welds, Fi – flanges, Ci – simulated corrosion defects, Ni – notches, and H – drilled holes where i = 1, 2, 3, etc. The size of the simulated defects is described in Table 1.

The data given in Figure 7 were taken with the MsS placed approximately 74 feet from Flange 1 (F1). The data in the top were obtained by directing the wave toward F1; the data in the bottom were obtained by directing the wave toward F2. The signals from each geometric feature and simulated defect were indicated in the data by using the respective symbols for them. The flange signals indicated in the parenthesis were caused by the small imperfection in the wave direction control of the MsS.

Except for N4 whose signal was not detectable, all simulated defects placed in the pipeline were detectable in the data. The data in Figure 7 demonstrate clearly the ability of inspecting a long length of pipe from a single test location using guided waves. For inspection of liquid-filled pipelines, T mode is better than L mode because of the absence of liquid-effect that causes extraneous signals in L mode data [10].

3.1.2 Inspection of U-Bend Tube

Figure 8 shows data that were obtained using a 64-kHz T mode guided wave from a 19.2-foot-long, 0.75-inch-OD, 0.087-inch-wall, U-bend tube. The configuration of the tube is illustrated on the top of the figure where symbols Ei (i = 1, 2) stand for end of tube. The radius of the U-bend was 3 inches and there were two notches (N1 and N2) whose cross-sectional area was approximately 7.4% and 23% of the total tube wall cross section, respectively. The data were taken with the MsS placed at approximately 0.9-foot from E1. The signals from each geometric feature and simulated defect were indicated in the data by using the respective symbols for them. The signals indicated as N1E1 and N2E1 were notch signals that were reflected back from E1.

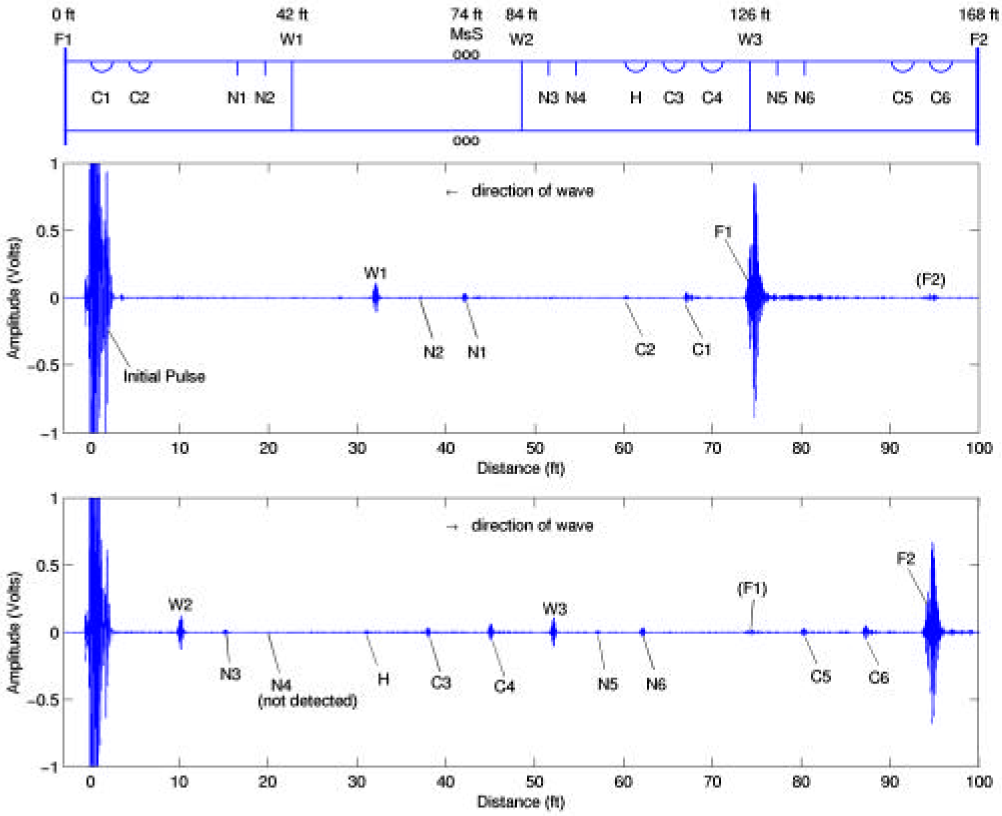


Figure 7. 35-kHz T-mode guided wave data obtained from a 168-foot-long, 4.5-inch-OD, water-filled pipeline

Table 1. Description of Defects (from left to right in the pipeline)

DEFECT	DIAMETER	LENGTH	DEPTH	AREA[a]
C1	4 Inches		25% Wall	6.7%
C2	0.5 Inch		50% Wall	1.0%
N1		4 Inches	25% Wall	7.3%
N2		0.5 Inch	50% Wall	1.0%
N3		1.0 Inch	50% Wall	3.1%
N4		1.0 Inch	50% Wall	1.6%
H	0.2 Inch (3 ea)		41% Wall	1.5% total
C3	1 Inch		25% Wall	1.6%
C4	1 Inch		50% Wall	3.1%
N5		2 Inches	25% Wall	3.5%
N6		2 Inches	50% Wall	6.7%
C5	2 Inches		25% Wall	3.0%
C6	2 Inches		50% Wall	5.2%

[a]Defect cross-sectional area relative to the pipewall cross-sectional area

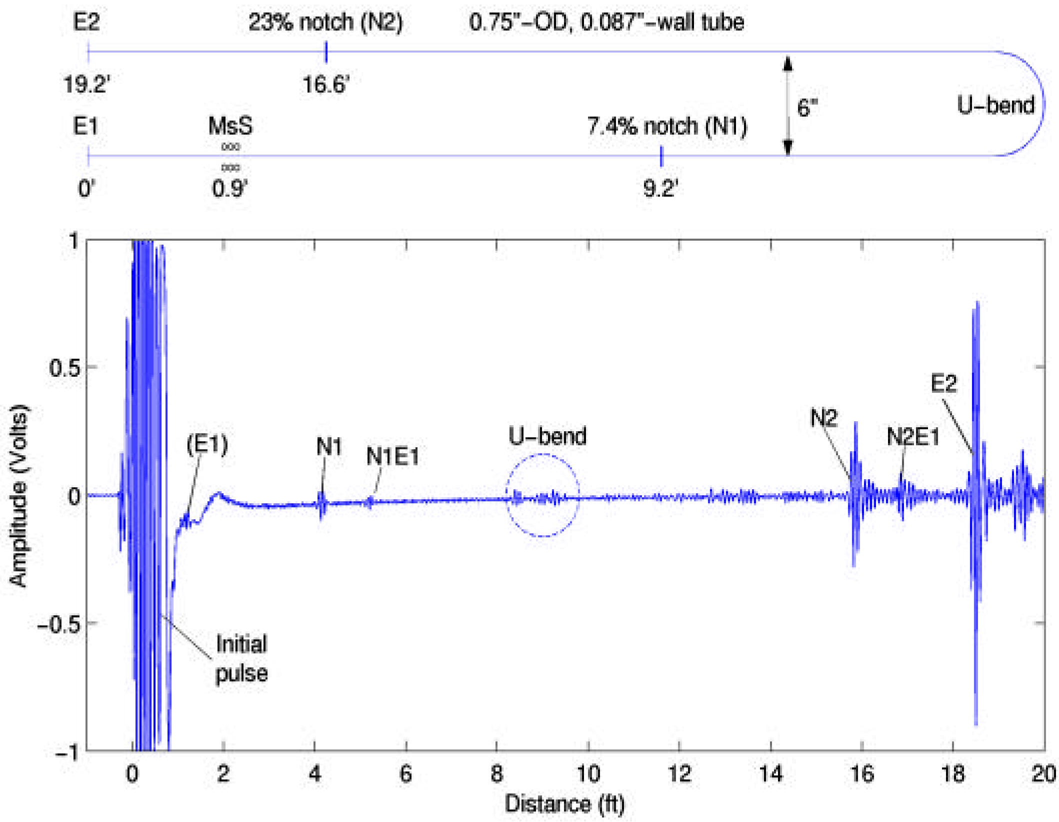


Figure 8. 65-kHz T-mode guided wave data obtained from a 19.2-foot-long, 0.75-inch-OD, U-bend tube

The data in Figure 8 show that, despite the short bend radius, the guided waves propagated around the U-bend without significant wave reflection and were able to inspect the entire length of U-bend tube from one end of the tube.

3.2 Plate-Type Structures

3.2.1 Inspection of Large Steel Plate

Figure 9 shows data that were obtained using a 128-kHz SH mode guided wave from a 0.25-inch-thick, 4 x 20 ft size steel plate as illustrated on the top of the figure. The upper trace data was obtained with the MsS placed near a side of the plate so that the notch would be outside of the guided wave beam. The lower trace data was obtained with the MsS placed at the center of the plate width so that the notch would face the guided wave beam at the normal angle.

The example data in Figure 9 clearly show the guided wave's ability to inspect a large area of a plate from a single sensor location. By incrementing the sensor position and repeating the inspection, a large plate structure such as above ground storage tanks or containment liners in nuclear power plants could be quickly inspected using the long-range guided wave inspection techniques.

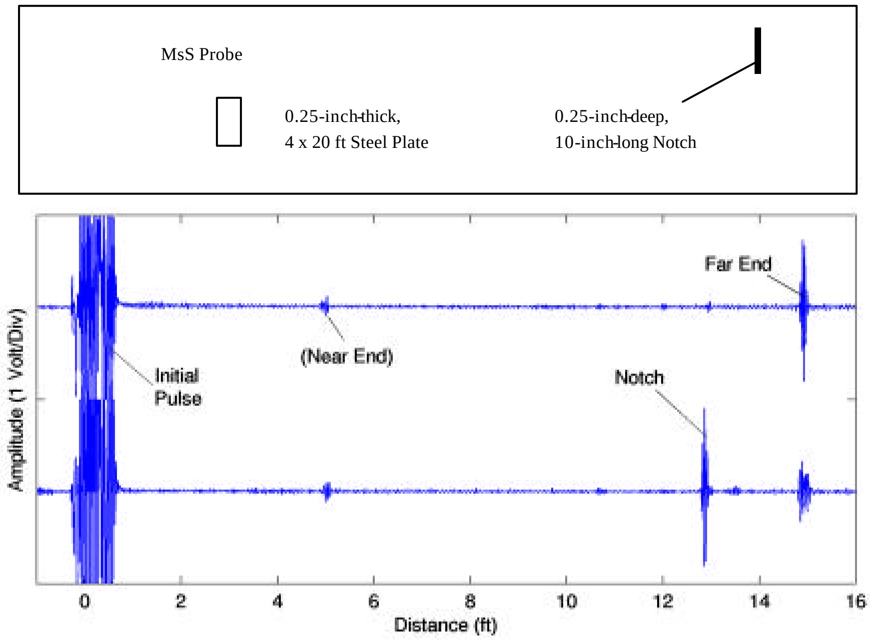


Figure 9. 128-kHz SH mode guided wave data obtained from a 0.25-inch -thick, 4- x 20-foot steel plate

3.2.2 Inspection Around Pipe Circumference

Figure 10 shows data that were obtained using a 100-kHz SH wave from a 24-inch-OD, 0.562-inch-wall pipe by propagating the guided waves around the pipe circumference as illustrated on the top of the figure. The upper trace data were obtained from a good region and the signals occurring at regular intervals are those caused by the initially generated wave revolving around the pipe circumference. The lower trace data were obtained from a region that contained a 0.125-inch-deep and 4-inch-long notch. In this case, in addition to the regular revolving signals, signals reflected from the defect are also present in the data. [Note: Since the waves were propagating in both clockwise and counter-clockwise directions, a single notch produced two defect signals. The circumferential location of the defect can be determined from the time difference between the regular revolving signals and the defect signals.]

The data in Figure 10 thus demonstrate the guided wave's ability to inspect the entire pipe circumference from a single sensor location. The guided waves are therefore very useful for inspecting pipes at pipe supports for wall loss due to erosion and corrosion. The guided waves are expected to be also very useful for in-line inspection of buried pipelines.

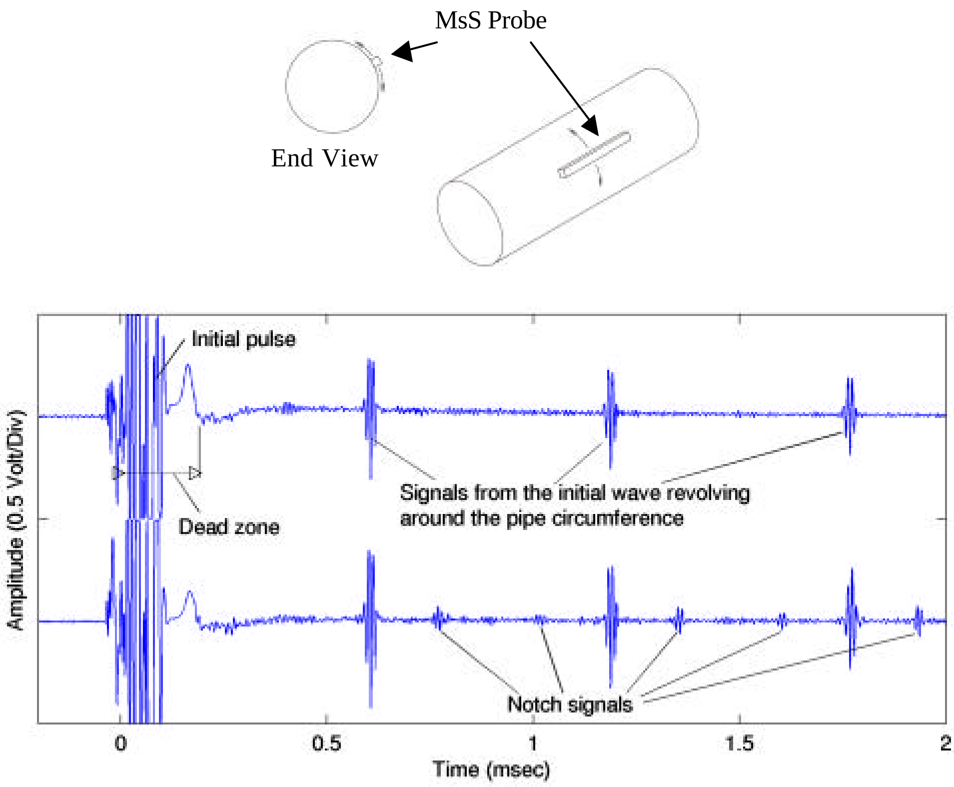
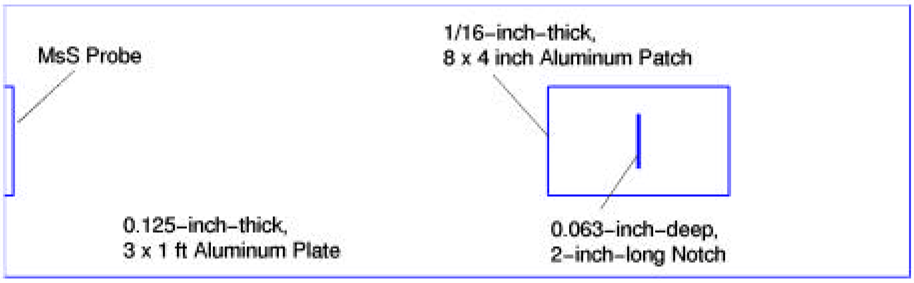


Figure 10. 100-kHz SH mode guided wave data obtained from a 24-inch-OD, 0.562-inch-wall pipe by propagating the wave around the pipe circumference

3.2.3 Inspection of Aluminum Plate

Figure 11 shows data that were obtained using a 128-kHz SH wave from a 0.125-inch-thick, 1 x 3 ft size aluminum plate illustrated on the top of the figure. The plate contained a 0.063-inch-deep and 2-inch-long notch that was patched over with a 1/16-inch-thick, 4 x 8 inch size aluminum plate using epoxy. The plate MsS probe was placed near one end of the plate over a thin nickel strip that was bonded to the aluminum plate. The data showed the signals that were reflected from the front and back ends of the aluminum patch, the notch, and the far end of the aluminum plate. Although not shown in this paper, the signals from the patch decreased significantly when the bonding between the patch and the substrate aluminum plate was degraded. The data in Figure 11 show the potential usefulness of the guided waves for long-range inspection and monitoring of aluminum structures in aircrafts for detection of cracks, corrosion, and bonding degradation.



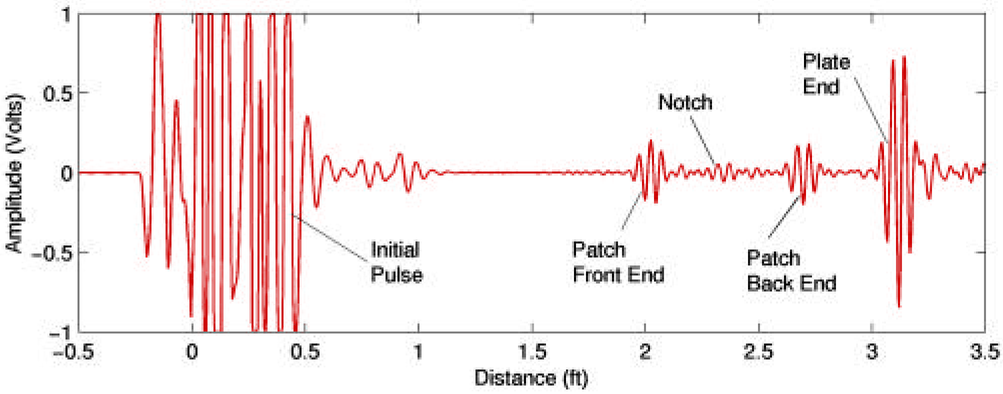


Figure 11. 128-kHz SH mode guided wave data obtained from a 0.125-inch-thick, 1 x 3 foot aluminum plate with a patch

4. CONCLUSIONS

Guided waves under a few hundred kHz are very useful for quickly inspecting a large and global area of a structure for defects from a single test location. The MsS technology is a guided-wave tool well suited for long-range inspection and testing of both cylindrical and plate-type structures such as piping, tubing, vessels, plates, and cables. The MsS technology is finding wide industrial applications in various industries including oil, gas, chemical, petrochemical, aerospace, electric power, and civil engineering where the long-range global inspection and monitoring is beneficial for maintaining the safety and integrity of the structure. Because the MsS is non-contact, it is also finding various applications in steel manufacturing industry for process control. As the industrial acceptance of the guided wave inspection technology increases, further active research and development of theory, modeling, probe and instrument system, and inspection and data processing techniques are expected to follow.

5. REFERENCES

1. M. Redwood, Mechanical Wave-guides, The Propagation of Acoustic and Ultrasonic Waves in Fluids and Solids with Boundaries, Pergamon, New York (1960).

2. J. D. Achenbach, Wave Propagation in Elastic Solids, Elsevier, New York (1975).

3. U.S. Patent Nos. 5,456,113, 5,457,994, 5,581,037, 5,767,766, 5,821,430, 6,212,944, and pending patents.

4. H. Kwun and C. M. Teller, "Detection of Fractured Wires in Steel Cables Using Magnetostrictive Sensors," Mat. Eval. 52, pp. 503-507 (1994).

5. C. M. Teller and H. Kwun, "New Methods for Inspecting and Monitoring Bridge Structures Using Magnetostrictive Sensors," Review of Progress in Quantitative NDE, Vol. 13, pp. 2147-2153, Plenum, New York (1994).

6. H. Kwun and A. E. Holt, "Feasibility of Underlagging Corrosion Detection in Steel Pipe Using the Magnetostrictive Sensor Technique," NDT&E International 28, pp. 211-214 (1995).

7. H. Kwun and K. A. Bartels, "Magnetostrictive Sensor Technology and Its Applications," Ultrasonics 36, pp. 171-178 (1998).

8. H. Kwun and C. Dynes, "Long-Range Guided Wave Inspection of Pipe Using the Magnetostrictive Sensor Technology – Feasibility of Defect Characterization," Nondestructive Evaluation of Utilities and Pipelines II, International Society for Optical Engineering (SPIE), SPIE Vol. 3400, pp. 326-337 (1998).

9. H. Kwun and S. Y. Kim, "Long-Range Guided-Wave Inspection of Steel Plates Using Magnetostrictive Sensors," Proc. 2nd International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, Vol. 3, pp. C421-C435, EPRI, Palo Alto, California (2000).

10. H. Kwun, K. A. Bartels, and C. Dynes, "Dispersion of Longitudinal Waves Propagating in Liquid-Filled Cylindrical Shells," J. Acoust. Soc. Am. 105, pp. 2601-2611 (1999).

6. ACKNOWLEDGEMENT

The authors wish to acknowledge the technical discussions and support from Jay Fisher, Ron Peterson, Chris Dynes, Cris Schwartz, Robert Spinks, Gary Hendrix, Gary Asher, and Louis Mendoza.