4th Middle East NDT Conference and Exhibition, Kingdom of Bahrain, Dec 2007
For all papers of this publication click: www.ndt.net/search/docs.php3?MainSource=57

REVIEW PAPER ON APPLICATIONS OF MAGNETOSTRICTIVE SENSOR TECHNOLOGY

Glenn M. Light, Ph.D., Hegeon Kwun, Ph.D., Sang Y. Kim, Ph.D., and Albert Parvin
Southwest Research Institute®
6220 Culebra Road
San Antonio, TX 78238

1. ABSTRACT

The magnetostrictive sensor (MsS) technology using thin ferromagnetic strips (such as nickel or FeCo) was developed by Southwest Research Institute (SwRI®)in early 2000 and has been used successfully in the petrochemical industry to inspect and monitor piping systems for corrosion and cracking. This technology generates a torsional mode guided wave that propagates in the pipe wall up to 500 feet from one location and can detect defects on the order of 0.5-1.0% of the total pipe wall cross section in the monitoring mode. The sensor consists of the ferromagnetic material (approximately 0.1 mm thick) by 25.4 mm wide bonded to the pipe and excited using an RF voltage passing through a ribbon cable. This provides a low profile, inexpensive sensor that can be left in place on the pipe or component for many years. By using FeCo strips with appropriate bonding materials and coil components, the MsS technology can be used on piping and components up to approximately 300°C.

Applications to piping, heat exchangers, and plate will be described. Results obtained from various example applications will be discussed. In addition, concepts for monitoring heat exchanger shells and other pressure vessels will also be discussed.

2. INTRODUCTION

SwRI has been using the MsS technology to generate guided wave in various materials and components as a means to inspect the materials and components for defects. Guided waves are mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bonded medium (such as pipe, plate, and rod) parallel to the plane. Although MsS can be used to generate guided waves directly into a ferromagnetic material, the most common embodiment of the MsS technology consists of a sensor (a coil and a ferromagnetic strip material) that generates (based upon the Joule effect) and detects (based on the Villari effect) guided waves electromagnetically in the ferromagnetic strip. The ferromagnetic strip is either bonded to a component or compressed against the component using an air bladder concept. A schematic diagram of the MsS with bonded strip material and associated instruments (Model MsSR3030) for generation and detection of guided waves is illustrated in Figure 1. For cylindrical objects (such as rod, tube, or pipe), the MsS is ring-shaped and utilizes a coil that encircles the object. For plate-like objects, the MsS is rectangular-shaped and utilizes either a coil wound on a U-shaped core or a flat coil.

4th Middle East NDT Conference and Exhibition, Kingdom of Bahrain, Dec 2007
For all papers of this publication click: www.ndt.net/search/docs.php3?MainSource=57

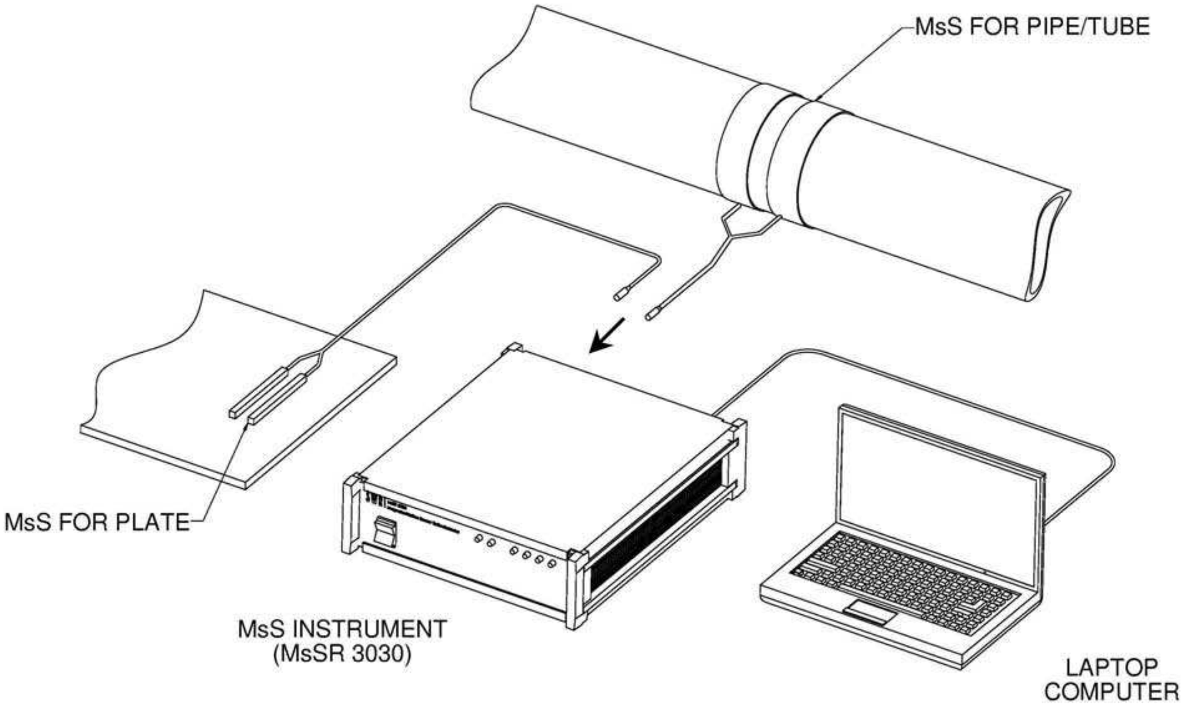


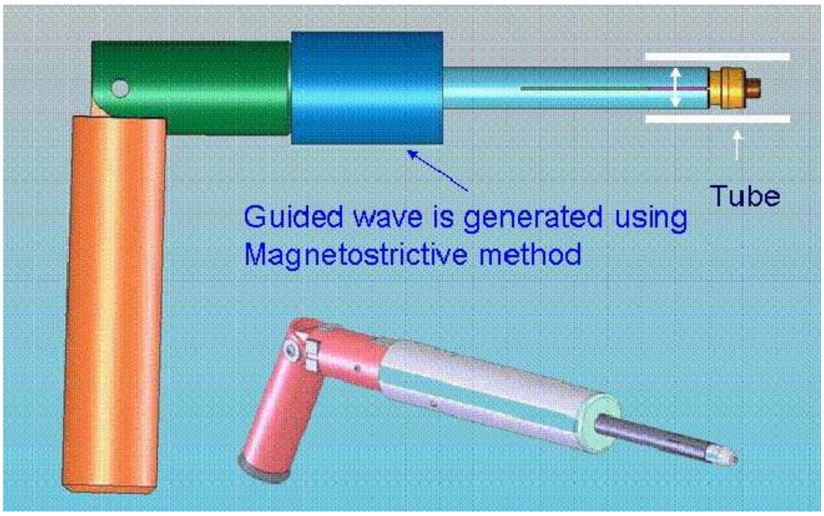
Figure 1.

Single MsS generates and detects the guided waves propagating in both directions. In practical inspection applications, the guided wave generation and detection are controlled to work primarily in one direction so that the area of the structure on either side of the sensor can be separately inspected. The wave direction control is achieved by employing two sensors, located side by side (as shown in Figure 1), and the phased-array principle in the MsS instrument.

For application to heat exchangers, the ferromagnetic material with excitation coil is placed at the end of a small diameter tube, with the other end of the small diameter tube slit. The guided wave is propagated along the small diameter tube. A cone is pulled through the slit portion of the tube so that it spreads to a large diameter. When the tube is placed in a heat exchanger and the cone is pulled, the slit tube expands to the diameter of the heat exchanger and the guided wave couples into the heat exchanger. This is illustrated in Figure 2 with a more realistic version of the actual heat exchanger probe shown in the lower portion of Figure 2.

Figure 2.

Monitoring is accomplished by leaving the MsS in place, collecting data periodically, and processing the data. Since the sensor is fixed, the waveform processing is fairly simple. In addition, leaving the sensor in place is practical because the cost of the sensor is low.



For long-range guided wave inspection and monitoring, a short pulse of guided waves in relatively low frequencies (up to a few hundred kHz) is launched along the structure under inspection, and signals reflected from geometric irregularities in the structure such as welds and defects are detected in the pulse-echo mode. From the time of flight of the defect signal and the signal amplitude, the axial location and approximate severity of the defect are determined.

Because of low wave attenuation (at 100 kHz, typically no more than approximately 0.33 dB/m in bare pipe and approximately 0.1 dB/m in bare plate; plate has a higher wave attenuation because of the beam spreading that is absent in pipe), guided waves afford inspection of a long length of structure from a single sensor location. The typically achievable inspection range is up to 200 m in above ground bare pipe (depending on pipe diameter and coating) and 10 m or more in bare plate. Within the inspection range, the cross-sectional area of detectable defect size in pipes by using the MsS is typically 2 to 3 percent of the total pipe-wall cross section or larger. In plates, it is typically 5 percent of the guided wave beam size or larger.

Because of the long-inspection range and good sensitivity to defects, guided-wave inspection technology such as the MsS is very useful for quickly surveying and monitoring a large area of structure for defects, including areas that are difficult to access from a remotely accessible location.

Because of convenience and better performance, the MsS technology now operates primarily in the T wave mode for piping inspection and in the SH wave mode for plate inspection by utilizing the thin ferromagnetic layer approach for generation and detection discussed in the previous section.

The thin ferromagnetic layer approach of the MsS technology has also shown a high potential for application to long-term structural health monitoring [1,2]. In this application, the MsS is permanently fixed to the structure. Guided wave data are then periodically obtained from the structure and compared with the initial data taken at the time of sensor installation. From the changes in the data, structural degradation such as defect formation and growth and its location in the structure are determined for assessment of structural condition and determination of suit-able maintenance measures.

As the changes in the data are more readily identified, the sensitivity of defect detection is significantly improved (by a factor of 5 to 10) in the monitoring mode over the inspection mode. Also, because the sensor is already in place on the structure, the time and cost for periodically acquiring data are minimal. Since the guided waves can inspect and monitor large areas of structure and the MsS is rugged and inexpensive, the MsS offers an ideal sensing approach for long-term structural health monitoring applications. Table 1 summarizes the capabilities and limitations of the present MsS technology for long-range piping inspection in bare pipes.

Presently, the MsS technology uses the T-wave mode primarily for piping inspection and monitoring because (1) the fundamental T-wave mode is not dispersive and, therefore, no consideration is necessary for possible dispersion effects that exist in the L-wave mode; (2) the T-wave MsS has fewer effects than other extraneous wave modes and, therefore, it gives better signal-to-noise ratio and its data are easier to analyze; (3) the T-wave does not interact with liquid inside the pipe and (4) the T-wave MsS does not require heavy bias magnets. The disadvantage of the T-wave MsS is the requirement for direct physical access to the pipe surface for bonding of the thin ferromagnetic layer. Therefore, to apply the T-mode MsS for bitumen-coated piping, for example, the coating must be removed beforehand, whereas the L-mode MsS can be applied without removing the coating. However, the advantage of the T-mode MsS greatly outweighs the disadvantage and, consequently, the T-mode MsS is used primarily for long-range piping inspection.

Recent work at SwRI has shown the ability to use the FeCo MsS sensors at temperatures of approximately 300°C. With the application of thin film technologies to the fabrication of the MsS, it is possible to achieve sensors that can work at temperatures as high as 650°C [3].

Table 1. Capabilities and Limitations of Present MsS System for Piping Inspection

Item	Capabilities/Limitations	Remarks
Dead Zone	14 inches (35 cm) at 32-kHz T-wave, 7 inches (18cm) at 64KHz T-mode	Using a two-cycle pulse; will vary with frequency and number of cycles in pulse
Defect Location	Axial location within ±1 inch (2.5 cm) at 64-KHz T-wave	Cannot determine circumferential orientation
Spatial Resolution (detecting two axially separated defects)	3.5 inches (9 cm) at 64-kHz T-wave	Using a two-cycle pulse; will vary with frequency and number of cycles in pulse
Pipe Material	Any material	For nonferrous pipe, a thin nickel strip is bonded
Pipe Size	Up to 24-inch (610-mm) diameter and less than 0.5-inch wall thickness	Outside the range, performance will be reduced due to lower MsS sensitivity
Inspection Range	300 feet (100 m) or greater	In bare, straight pipe in good surface condition
Detectable Defect Type	Isolated corrosion pits and circumferential cracks	Longitudinal defects could also be detectable if their circumferential cross section exceeds minimum detectable defect size and/or the defect is fairly deep
Minimum Detectable Defect Size	2 to 3% of pipewall cross section	Isolated defects in pipes with otherwise good surface condition; varies with fre-quency and defect shape

Defect Characterization	Limited to rough estimation of circumferential cross section	Cannot determine depth, width, and length, whether it is on OD or ID

3. EXAMPLE APPLICATIONS

To show the MsS system capability including the system software for data analysis, 32-kHz T-wave data obtained from a water filled pipeline sample are given in Figure 3, together with a schematic diagram of the pipeline configuration. The sample was 168 mm in outside diameter with a 7.1 mm wall and was approximately 44 m long with a 90-degree elbow. One end of the pipeline was flanged. The sample contained several simulated corrosion defects placed at various locations along the pipe. The data were acquired with the MsS positioned at approxi-mately 11.3 m from the flanged end. The upper data were obtained by launching the guided wave to the positive side of the sensor (i.e., toward the elbow) and the lower data to the negative side of the sensor (i.e., toward the flange), respectively.

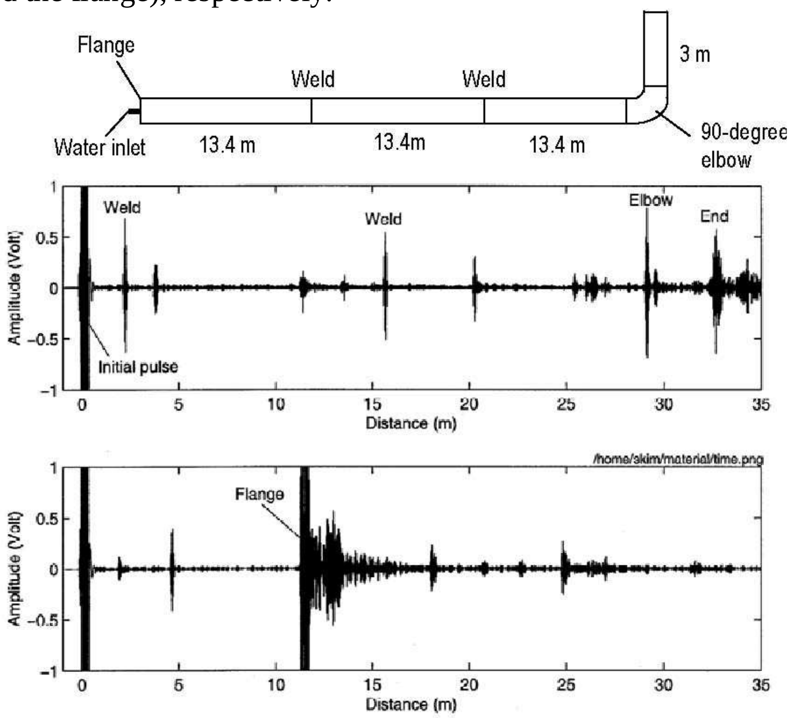
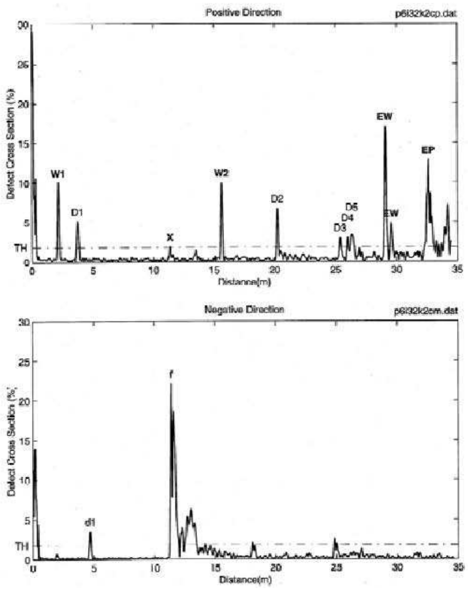


Figure 3.

Figure 4 shows the processed data and inspection report generated by the system software after the data analysis. The computer reads in the acquired rf data files from both sides, calculates the wave attenuation and velocity, corrects the attenuation effects, converts the data to video data, detects signals that exceeds the preset threshold, identifies and characterizes the detected signals, and generates a preliminary inspection report for the inspector's final review and approval. All of the above are automatically performed by the system computer within a few minutes. The inspector then reviews the computer analysis results, confirms and corrects, if necessary, and finalizes and approves the results for reporting.



Inspection Report

02-May-2002

Inspector: Bob Spinks
Location: SwRI
Pipe: 168-mm-OD. 7.1-mm-wall Steel Pipe
Velocity: 3.221 m/msec
Attenuation: 0.054 dB/m
Threshold: 1.8 % Defect
Assumption ---> Weld Signal: 10.0 % Defect

Frequency: 32 kHz
Cycles: 2
Gain: 24 dB
Filter: 32 kHz
Sampling Freq.: 1.0 MHz

Positive Direction p6i32k2cp.dat

No.	Symbol	Dist.	% Defect	Class	Comments
1	W1	2.17	10.00	Weld	
2	D1	3.75	5.11	Defect	
3	X	11.37	1.87	Directionality	
4	W2	15.62	10.00	Weld	
5	D2	20.22	6.72	Defect	
6	D3	25.36	2.96	Defect	
7	D4	25.98	3.05	Defect	
8	D5	26.33	3.39	Defect	
9	EW	29.07	17.08	Elbow Weld	90-degree elbow
10	EW	29.53	4.84	Elbow Weld	90-degree elbow
11	EP	32.63	12.87	End of Pipe	

Negative Direction p6i32k2cm.dat

No.	Symbol	Dist.	% Defect	Class	Comments
1	d1	4.71	3.50	Defect	
2	f	11.39	22.11	Flange	

Figure 4.

All the defects placed on the sample were simulated corrosion defects with rounded con-tours of varying sizes. Specifics of the defects are presented in Table 2. In the table, the cross-sectional area refers to the maximum cross section of the defect relative to the total pipe-wall cross section.

Table 2. Defects Placed on the Pipeline Sample and their Sizes

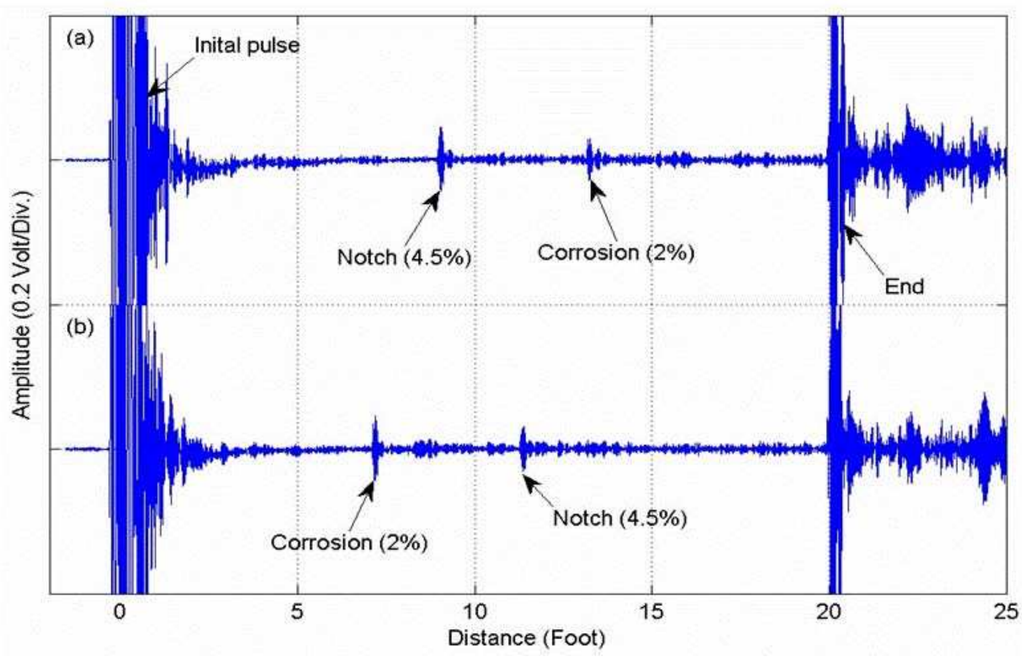
Defect	Overall Size and Shape	Cross-Sectional Area (%)	Comments
D1	10 x 15-cm rectangle	6.3	Irregular cross section, longer along the pipe length
D2	10 x 15-cm ellipse	8.5	Longer along the pipe length
D3	51-mm-diameter circle	3.7	
D4	41-mm-diameter circle	3.0	
D5	28-mm-diameter circle	2.1	D5 and D6 were separated by 15 cm and detected as a single defect in Figure 6
D6	28-mm-diameter circle	2.1	
d1	Three 28-mm-diameter circles	6.3	Three defects distributed around the pipe

The % defect in the inspection report in Figure 4 was determined by assuming that: (1) the weld signal is equivalent to 10% defect and (2) the signal amplitude is linearly proportional to the cross-sectional area of the defect. The above assumptions are not exactly accurate because weld varies from pipe to pipe and from location to location and the defect signal amplitude and waveform vary with the actual contour and shape of the defect. As a first-order approximation, however, the assumptions used in the data analysis are reasonable as can be seen in the similarity between the values of the actual cross-sectional area in Table 2 and the estimated % defect in the inspection report in Figure 4.

An example of heat exchanger data is shown in Figure 5 for data collected from a U-bend tube. The defects are easily seen and the U-bend (at 10 feet) does not affect the signal.

Figure 5.

Because the MsS are inexpensive and can be left in place, a single MsS instrument could be used to monitor many locations. As an extension of this technology, SwRI is developing an MsS multiplexer that will allow many MsS probes to be connected to one instrument. With appropriate power, data analysis and management software, and communication technologies, engineers will, in the future, have the ability to receive warnings when early stages of damage are occurring. SwRI is presently developing many of these applications. One application is illustrated in Figure 6 where multiple MsS probes are connected to a multiplexer and base station control system.



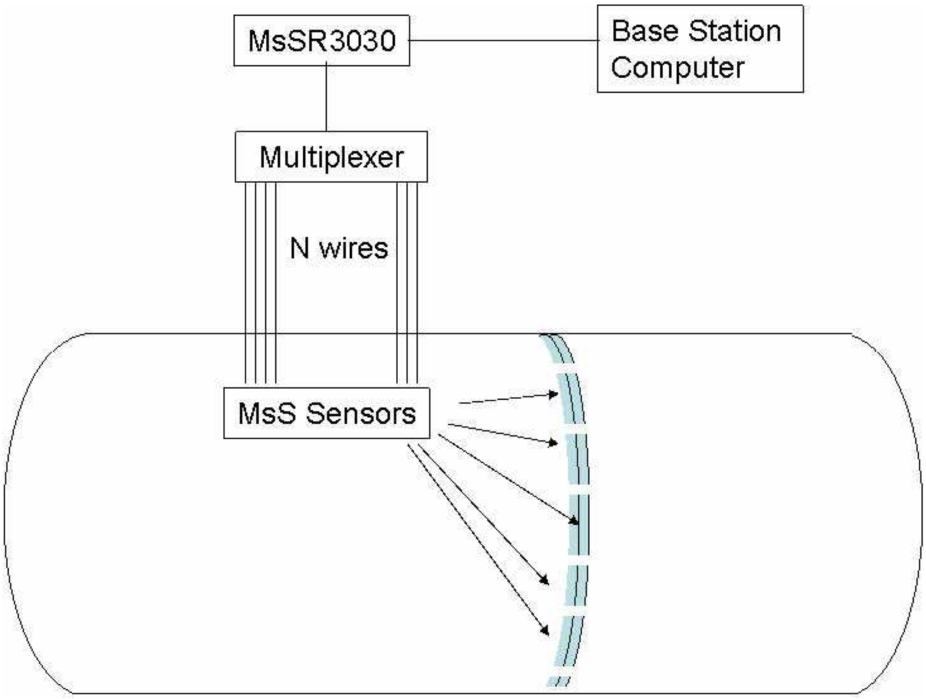


Figure 6.

4. CONCLUSIONS

Guided waves under a few hundred kHz are very useful for quickly inspecting and monitoring 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 long-term monitoring of both cylindrical and plate-type structures such as piping, 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 long-range global inspection and monitoring are beneficial for maintaining the safety and integrity of the structure. As the industrial acceptance of the guided wave inspection technology increases, active research and development of the guided wave theory, modeling, probe and instrument system, and inspection and data processing techniques are expected to continue for further advancement of the technology.

5. REFERENCES

1. Kwun, H., G. M. Light, S. Y. Kim, R. H. Peterson, and R. L. Spinks, “Permanently Installable, Active Guided-Wave Sensor for Structural Health Monitoring,” *Proceedings of the First European Workshop on Structural Health Monitoring*, Paris, July 10–12, 2002.
2. Kwun, H., 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).
3. Light, G., S. Hudak, B. Lanning, “Thin Film Magnetostrictive Sensor for Inspection in Temperature Environments of 500°F,” *Proceedings of the ASNT Spring NDE Research Symposium*, Orlando, Fl, April 2006.

6. LIST OF FIGURES

4th Middle East NDT Conference and Exhibition, Kingdom of Bahrain, Dec 2007
For all papers of this publication click: www.ndt.net/search/docs.php3?MainSource=57

analysis

Figure 5. Example of heat exchanger data

Figure 6. Example of multiple MsS probes connected to a multiplexer and base station control system