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FYI

Magnetostrictive Sensor Technology for Long-Range Guided Wave Inspection and Monitoring of Pipe

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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 (Achenbach 1973, Redwood 1960). 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 wave frequency and geometry of the medium. In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders.

In pipe, the guided waves exist in three different wave modes — longitudinal (L), torsional (T) and flexural (F). Although the properties of guided waves are complex, with judicious selection and proper control of wave mode and frequency, the guided waves can be used to achieve 100% volumetric inspection of a large area of a structure from a single sensor location.

Guided waves have wavelengths that are large compared to the wall thickness of the part being inspected. Guided waves can be generated using piezoelectric transducers, electromagnetic acoustic transducers (EMAT) or magnetostrictive sensors (MsS). This paper focuses on the use of the MsS technology.

The MsS generates and detects guided waves electromagnetically in the material under testing. For wave generation, it relies on the magnetostrictive (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 an externally applied magnetic field. For wave detection, it relies on the inverse-magnetostrictive (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 a *magnetostrictive sensor*.

A schematic diagram of the sensor and associated instrumentation for generation and detection of guided waves are illustrated in Fig. 1. In the standard application, the sensor consists of a thin ferromagnetic material (such as nickel or an iron cobalt alloy) that is bonded to the pipe. A thin excitation coil is placed over the thin ferromagnetic material. The thin ferromagnetic material has a biasing magnetic field and the excitation coil is configured to apply a time-varying magnetic field to the ferromagnetic material. This generates a wave in the thin ferromagnetic material that is then coupled (usually by an epoxy bond) into the material being inspected. The same sensor is used to pick up magnetic induction changes in the material caused by the guided wave reflected by a discontinuity. A single magnetostrictive sensor 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 areas of the structure on either side of the sensor can be inspected separately. This technology can be also be used in plates, tubes and rods with slight differences in the probes.

In the long-range guided wave inspection, a short pulse of guided waves in relatively low frequencies (up to a few hundred kHz) is launched along the structure under inspection. Signals reflected from geometric

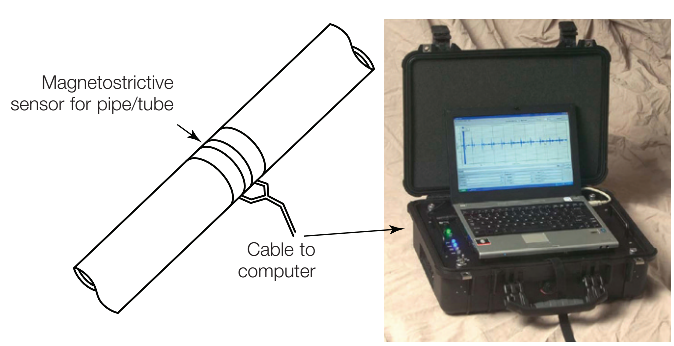

Figure 1. Magnetostrictive sensor and computer instrumentation.

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irregularities in the structure such as welds and discontinuities are detected in the pulse-echo mode. Axial location and severity of the discontinuity are determined by occurrence time of the discontinuity signal and the signal amplitude. The MsS technology uses the T wave mode primarily for piping inspection that is generated and detected with the thin ferromagnetic (typically iron cobalt) layer approach. Reasons for this practice include the following: (1) The fundamental T wave mode has a constant velocity (non-dispersive) and therefore, no consideration is necessary for the dispersion effects (broadening of waveform as the wave propagates) that exist in the L and F wave modes. (2) The T wave MsS generates and detects the particle displacement along the pipe circumference direction and is axial symmetric covering 360 degrees of the pipe circumference. The MsS generates less coherent background noise due to dispersive L and F waves generated by the piezoelectric systems. This provides a better signal-to-noise ratio and data that 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 and thus is much easier and safer to handle than its L wave counterpart.

A disadvantage of the T wave MsS is the requirement for direct physical access to the pipe surface for bonding of the thin ferromagnetic layer. For example, before the T mode MsS can be applied to bitumen-coated piping, the coating must first be removed whereas, the L mode MsS can be applied without removing the coating. However, the advantages of the T mode MsS greatly outweigh this limitation. As a result, it has become the primary wave mode for long-range piping inspection.

Because of low wave attenuation (at 100 kHz, typically no more than approximately 0.033 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. In bare pipe, the inspection range is typically 30 m (98 ft). In some cases, this can extend to 150 m (492 ft) or more. In bare plate, the inspection range can extend 10 m (33 ft) or more. Within the inspection range, the cross-sectional area of detectable discontinuity size in pipes by using the MsS is typically 0.5 to 5.0% of the total pipe-wall cross section. In the corrosion under insulation (CUI) application of chemical facilities, the detection threshold level is usually set at approximately 0.5 to 1.0% because these pipes are very clean and high-frequency guided wave signals have high signal-to-noise ratio. The magnetostrictive sensor software uses the variable threshold level and the lowest threshold level is usually 0.5% for good pipeline. When the pipe has a large amount of generalized corrosion, internal sludge build up, or the pipe is transporting very heavy, viscous material, the inspection range is decreased and the threshold level is increased.

Because of its long inspection range and good sensitivity to discontinuities, the MsS guided-wave inspection technology is very useful for quickly surveying large areas of a structure for discontinuities, including those areas that can only be accessed remotely.

The thin ferromagnetic layer approach of the MsS technology has also shown a high potential for application to long-term structural health monitoring (Kwun 2002). 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 changes in data, the formation and growth of discontinuities as well as their location in the structure can be determined. This information can be used to assess structural degradation and determine suitable maintenance measures. Because changes in the data are more readily identified in the monitoring mode, the sensitivity of discontinuity detection is significantly improved (by a factor of 5 to 10) over the inspection mode.

Examples of Piping Inspection Data and Analysis

To demonstrate the capabilities of the MsS system and system software for data analysis, a sample water-filled pipeline was used to collect data using a 32 kHz T wave. Figure 2 shows the pipeline configuration and data obtained. The sample pipeline was 168 mm (6.6 in.) in outside diameter with a 7.1 mm (0.3 in.) wall and was approximately 44 m (144 ft) long with a 90-degree elbow. One end of the pipeline was flanged. The sample contained several simulated corrosion discontinuities placed at various locations along the pipe. The data were acquired with the MsS positioned

FYI continued on p 8

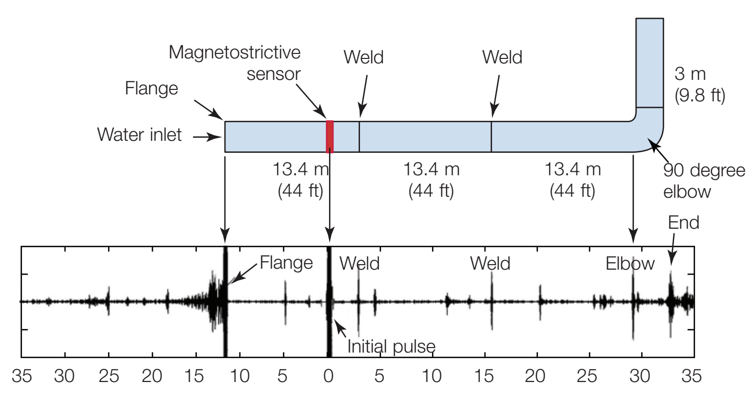

Figure 2. Water filled pipeline with magnetostrictive sensor and 32 kHz T wave data obtained from pipeline.

FYI continued from p 7

at approximately 11.3 m (37.1 ft.) from the flanged end. The upper data (Fig. 3a) were obtained by launching the guided wave toward the elbow (to the positive side of the sensor) and the lower data (Fig. 3b) were obtained by launching the guided wave toward the flange (to the negative side of the sensor).

Figures 3 and 4 show the processed data and inspection report generated by the system software after the data analysis. The computer reads in the acquired data files from both sides, calculates the wave attenuation and velocity, corrects the attenuation effects, converts the data to video data, detects signals that exceed the preset threshold, identifies and characterizes the detected signals and generates a preliminary inspection report for the inspector's final review and approval. The inspector then reviews the computer analysis results, confirms and corrects if necessary and finalizes and approves the results for reporting.

All the discontinuities placed on the sample simulated corrosion with rounded contours of varying sizes and with a maximum depth of approximately 50% of the pipe wall. The cross-sectional area refers to the maximum cross section of the discontinuity relative to the total pipe-wall cross section.

Conclusion

Guided waves under a few hundred kHz are very useful for quickly inspecting a large and global area of a structure for discontinuities 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 technology also has application for inspection of suspender ropes on highway suspension bridges and anchor rods (Khazem 2001), heat exchangers (Kwun 1998) and plates (EPRI 2000, Kwun 2000).

The MsS technology is finding wide industrial application 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 industrial acceptance of guided wave inspection technology increases, active research and development of guided wave theory, modeling, probe and instrument system and inspection and data processing techniques are expected to continue for further advancement of the technology.

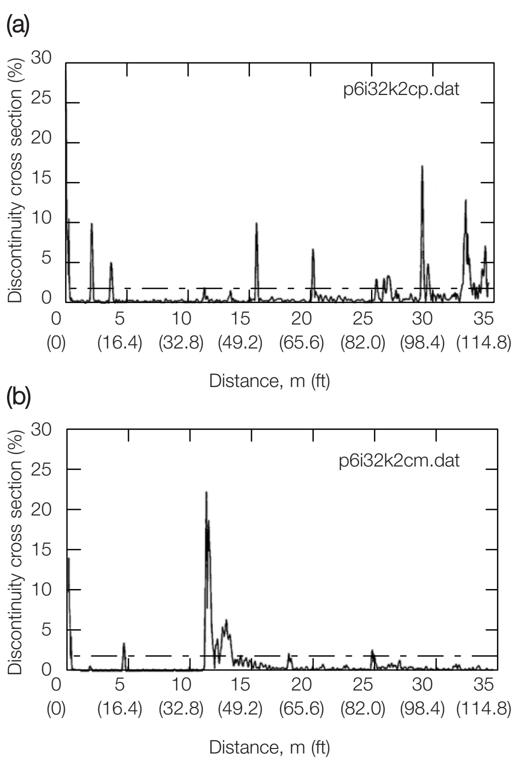

Figure 3. Computer analysis of magnetostrictive sensor data; (a) positive direction or toward elbow and (b) negative direction or toward flange. Dashed line is detection threshold. Any reflector below this level is not identified as an indication requiring further analysis.

Inspection Report

02-May-2002

Inspector:
Location:
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. Inspection report generated by system computer after analysis.

FYI continued from p 8

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