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INTRODUCTION

Heat exchangers (including steam generators, condensers, and coolers) are key equipment in processing plants such as refineries, chemical plants, and electric power generation plants. To minimize forced outages due to heat exchanger (HX) failures and associated loss of operating revenues and maintenance costs, HX tubes are inspected regularly. Primary tools used for HX tube inspections are eddy current and an ultrasonic tool called IRIS (Internal Rotary Inspection System). These techniques inspect one local area at a time and, thus, require scanning.

If a method exists that can rapidly survey individual tubes and rate their conditions such as good, marginal, and poor, the overall effectiveness of inspection/maintenance could be significantly improved. For example, tubes rated good need no additional testing; tubes rated marginal may be further examined using local inspection tools to obtain more detailed defect information for maintenance decision; tubes rated poor may be plugged without further examination. Also, if there are too many poor and marginal tubes, the HX may be replaced with no further inspection. By screening all tubes and quickly identifying tubes with potential problems and their numbers and distributions, inspection/maintenance decisions could be made more effectively, leading to enhanced HX reliability at a reduced overall inspection/maintenance cost.

A potential method for rapidly surveying HX tubes is the guided-wave inspection method.[1-4] Since guided waves can travel a long distance and examine the entire cross-sectional area of a tube, the entire length of individual tubes in HX could be tested for defects from one end of the tube without scanning. Recognizing its potential, various research groups have developed guided-wave probes for in-bore HX tube testing over the years, including torsional (T) mode probe based on electromagnetic acoustic transducer (EMAT)[2] and longitudinal (L) mode probe based on piezoelectric transducers.[4] Due to various technical difficulties and limitations, however, no practical guided-wave probes have been realized for in-bore testing of tubes. In comparison, practical probes for long-range guided-wave testing of piping from outside the pipe, whose development began more than a decade later, have been realized and in use for field applications.[5-7]

HEAT EXCHANGER PROBE

Figure 1 illustrates schematically the design of the T-mode guided-wave probe for in-bore tube testing. The probe consists of a hollow cylindrical waveguide, magnetostrictive sensor (MsS),[7] and drawbar mechanism. The MsS installed on the hollow cylindrical waveguide generates and detects T-waves in the waveguide. When in use, the waveguide is inserted into the tube being tested, and the tip of the waveguide is expanded by pulling the drawbar nose-piece into the waveguide to make intimate mechanical contact between the waveguide and inside surface of the tube being tested. To allow expansion of the waveguide at the tip, the tip area is longitudinally slit at several orientations around the waveguide circumference. The T-wave pulse generated by the MsS propagates toward the end of the waveguide inserted into the tube and is coupled to the tube through the mechanical contacts formed at the tip area, and then propagates along the length of the tube. Guided-wave signals reflected from the geometric irregularities in the tube, including defects and the far end of the tube, are detected by the MsS via the inverse process.

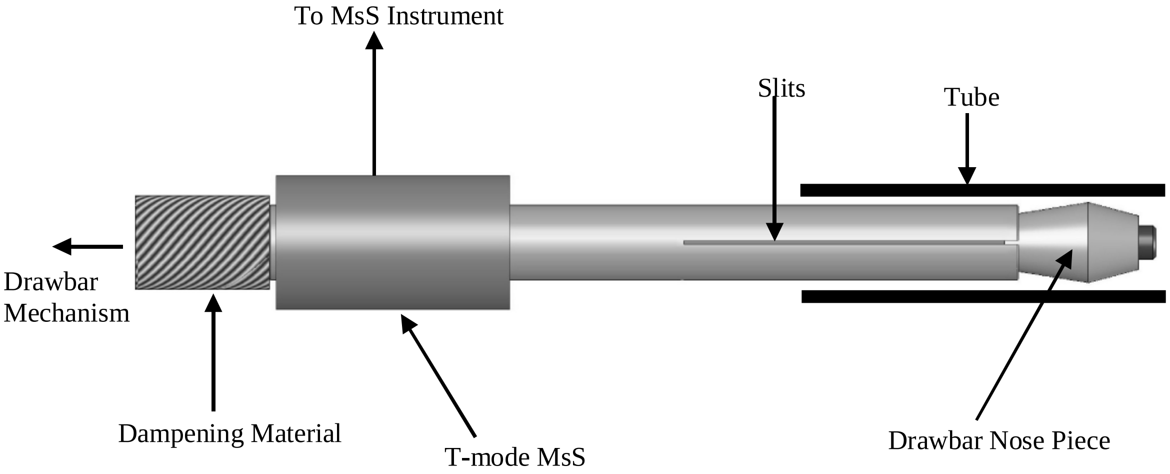

Figure 1: Design sketch of the T-mode guided-wave probe.

Damping material is placed on the opposite end of the waveguide (to the inserted end) to minimize wave reverberations in the waveguide of the probe.

In selecting design parameters such as the guided-wave mode and frequency for tube testing, various factors require careful consideration. The first factor is defect detection sensitivity. Tubes in heat exchangers typically range from 12.7 to 25.4 mm in outside diameter (OD). Because of the small tube size, defects that need to be detected are also relatively small. Since defect detection sensitivity is proportional to the ratio between the defect size and the wavelength, a sufficiently high-frequency wave is necessary to detect small defects in tubing. The second factor is the test range. The test range is inversely proportional to the wave frequency. The wave frequency, therefore, should be low enough so that the entire length of a tube could be examined from one end of the tube. The third factor is wave dispersion. To be useful for long-range testing applications, the wave should have minimal dispersion. Additional factors to consider include ease in wave mode control, test procedures, and data interpretation.

To illustrate why the T-mode is much superior to the L-mode for long-range guided-wave testing of tubes, dispersion curves of these modes in different sized tubes are plotted in Figure 2. Here, the dispersion curves are for tubes with a fixed wall-thickness and OD ratio (that is 0.08). As can be seen, the dispersion curves of L(0,1) and L(0,2) waves vary widely with frequency and tube size. The frequency regions where the L-mode is not highly dispersive and, thus, may be suitable for long-range testing is either too low in frequency to have sufficient defect detection sensitivity or too high in frequency to have sufficient test range. These frequency regions also vary with tube size, which would result in testing procedure variations. Also, in frequency regions where both L(0,1) and L(0,2) waves are present, wave mode control becomes more difficult. The dispersion curve of T(0,1) waves, on the other hand, is a straight line and changes neither with frequency nor with tube size. The T-mode is also easy to control and can be operated in any frequency region. The T-mode, therefore, has properties that are ideal for long-range guided-wave testing and is much superior to the L-mode for HX tube applications.

The guided-wave probe we have developed therefore uses the T-mode instead of the L-mode. Compromising between the defect detection sensitivity and the testing range, the probe has been designed and built to operate at 128 kHz. The wavelength of the T-mode at 128 kHz is approximately 2.54 cm in steel tubes.

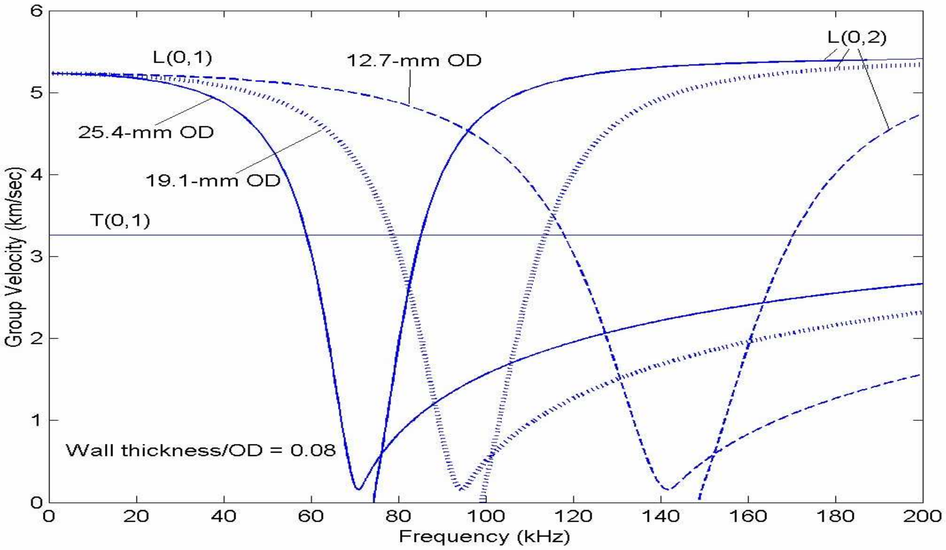

Figure 2: Dispersion curves of L- and T-mode waves in different sized tubes.

TEST EXAMPLES

U-Bend Tube Test Sample

Figure 3 shows an example of data obtained from a U-bend tube test sample using the developed T-mode guided-wave probe in the laboratory. The test sample was 19.1-mm OD, 2.1-mm wall, and approximately 6.1-m total length, with a 38-mm radius U-bend at mid-length. In the figure, 0 point in the distance corresponds to the tip of the probe's waveguide. The signals at and near the 0 distance point are those reflected from the probe tip and reverberating in the waveguide of the probe. The signal reflected from the far end of the tube is indicated as "end."

The dead zone caused by the tip-reflected and reverberating signals in the probe was approximately 50 cm. The signal-to-noise ratio (SNR) of the far-end-reflected signal was approximately 60 dB, indicating that the mechanical coupling of the T-mode between the probe waveguide and the tube is satisfactory for practical use. Despite the small bend radius, the bend area did not produce any noticeable signals and did not impair the wave propagation.

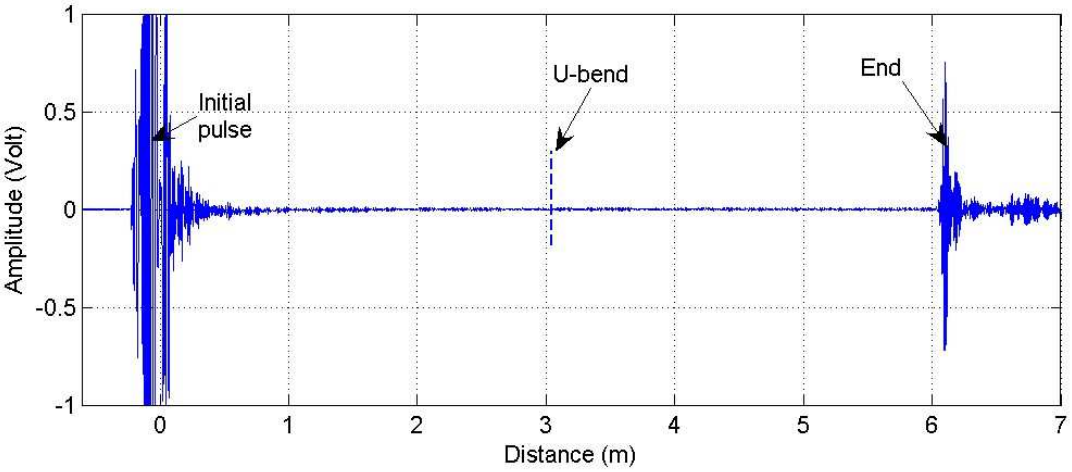

Figure 3: 128-kHz T-mode data obtained from a 19.1-mm-OD, 2.1-mm-wall steel tube with 38-mm radius U-bend.

Figure 4 shows data obtained from the same U-bend test sample after two artificial defects were placed in the sample near the U-bend, one on each side. One was a simulated corrosion wall loss area that was approximately 8 mm in diameter with the maximum depth of approximately 0.64 mm. The other was a circumferential notch that was approximately 8 mm long with the maximum depth of approximately 1.3 mm. The maximum cross-sectional area relative to the total tube wall cross-sectional area was approximately 2% for the corrosion defect and 4.5% for the notch. These defects are shown in Figure 5. Both defects were detectable from either end of the U-bend tube sample. The data in Figure 4 show that a long U-bend tube can be tested from one end of the tube and that relatively small defects in the tube are detectable.

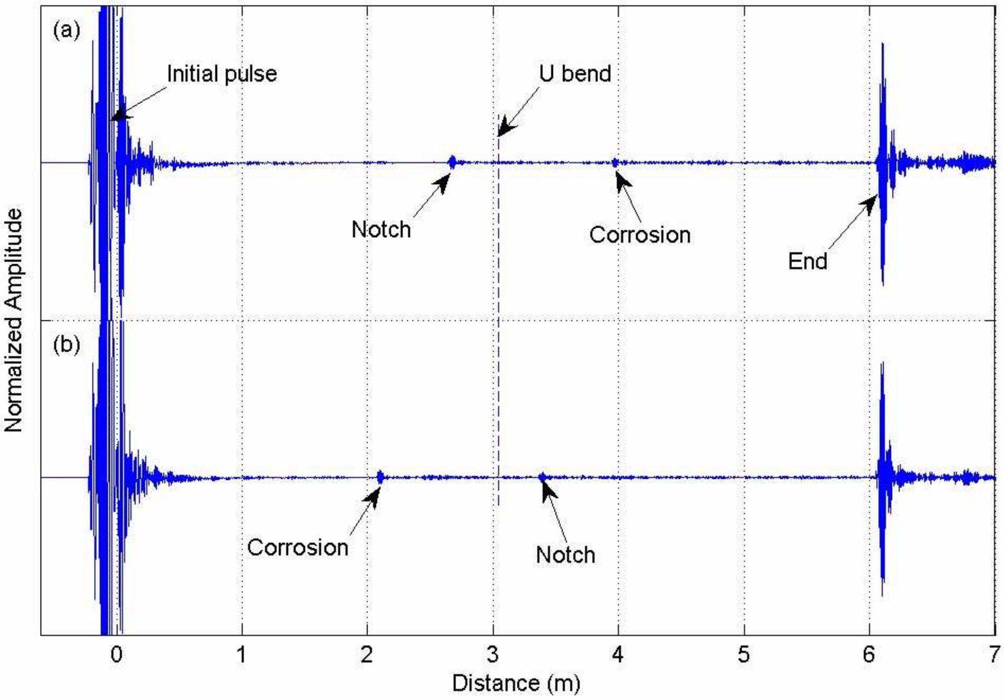

Figure 4: 128-kHz T-mode data obtained from either end of the 19.1-mm-OD, U-bend tube sample with simulated defects.


Notch (4.5% defect)

Corrosion (2% defect)

Figure 5: Pictures of the artificial defects used in the evaluation of MsS technology for heat exchanger tube inspection.

Tubes in a Heat Exchanger Mockup

The performance of the T-mode guided-wave probe was evaluated on 25.4-mm-OD, 0.7-to 0.9-mm-wall, carbon steel tubes in an HX mockup at the Electric Power Research Institute (EPRI) NDE Center in Charlotte, North Carolina. The mockup, designed for testing eddy current techniques, was 1.8 m long and contained a total of 28 straight tubes arrayed in a 16.5-cm x 19-cm square. The tubes were placed between a 25.4-mm-thick tube sheet at each end of the mockup through four 19.05-mm-thick support plates regularly spaced along the tube length. Some tubes in the mockup had no defects and some had various machined-in defects along the tube length.

Figure 6 shows examples of data obtained from the HX mockup by using a T-mode guided-wave probe made for 25.4-mm-OD, 1.3-mm-wall tubes. The top trace in the figure was from a tube with no defect. The second and third traces were from tubes with large defects. The bottom trace was from a tube containing small defects. As shown in the figure, defective tubes were readily distinguishable from good tubes, and the severity of tube conditions was readily determined. The data in Figure 6 thus demonstrate the capability of quickly surveying HX tubes and rating the general condition of each tube for subsequent inspection/maintenance decisions.

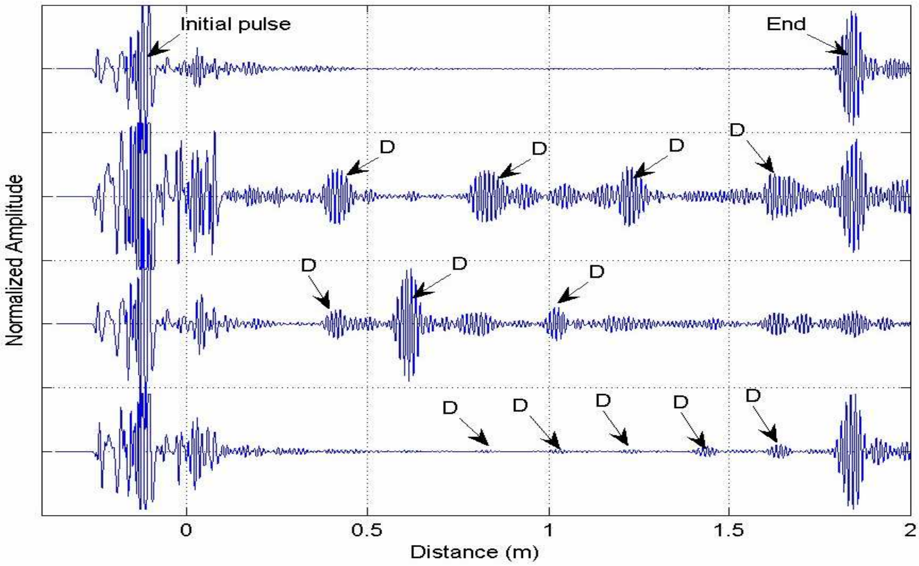

Figure 6: Examples of data obtained from tubes in an HX mockup.

Nonferrous Tubes

The T-mode guided-wave probe relies on the mechanical coupling for tube testing. Therefore, the probe can be used on tubes made of any material, including nonferrous tubes. An example of data from nonferrous tubes is given in Figure 7. The data were taken from a U-bend Inconel steam generator tube sample hung on a wall bracket at EPRI NDE Center. Since the tube was new, the signal was very clean. The small indication in the middle between the initial pulse and the end signals was from the bracket contact point at the U-bend. As can be seen in this example, the T-mode guided-wave probe is applicable to tubes of any material type.

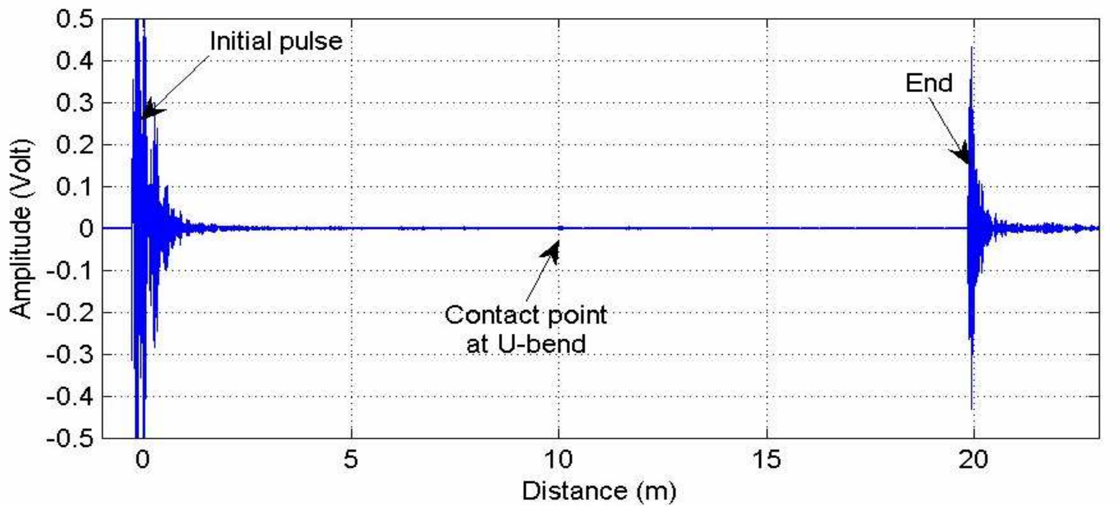

Figure 7: 128-kHz T-mode data from a U-bend Inconel steam generator tube.

SUMMARY

A torsional-mode guided-wave probe that was developed for long-range testing of heat exchanger tubing from the bore-side has been presented. Examples of test data obtained from various types of tubes, including U-bend tubes, ferrous and nonferrous tubes, and finned tubes, show that the probe is suitable for long-range testing for rapid survey and rating of tube conditions. The probe is robust and, thus, is fit for practical use in the field. Field evaluations and validation of the probe performance are being arranged to transfer the technology to the industry.

ACKNOWLEDGMENTS

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