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Development of a Novel Omnidirectional Magnetostrictive Transducer for Plate Applications

Sergey Vinogradov 1a, Adam Cobb 1b, Jonathan Bartlett 1c, Youichi Udagawa 2d

1 Sensor Systems and NDE Technology Section, Southwest Research Institute, San Antonio, Texas
2 IHI Inspection & Instrumentation Co., Ltd, Yokohama-city, Kanagawa, Japan

a)Corresponding author: sergey.vinogradov@swri.org
b)adam.cobb@swri.org
c)jonathan.bartlett@swri.org
d)y_udagawa@iic.ihi.co.jp

The application of guided waves for the testing of plate-type structures has been recently investigated by a number of research groups due to the ability of guided waves to detect corrosion in remote and hidden areas. Guided wave sensors for plate applications can be either directed (i.e., the waves propagate in a single direction) or omnidirectional. Each type has certain advantages and disadvantages. Omnidirectional sensors can inspect large areas from a single location, but it is challenging to define where a feature is located. Conversely, directed sensors can be used to precisely locate an indication, but have no sensitivity to flaws away from the wave propagation direction. This work describes a newly developed sensor that combines the strengths of both sensor types to create a novel omnidirectional transducer. The sensor transduction is based on a custom magnetostrictive transducer (MsT). In this new probe design, a directed, plate-application MsT with known characteristics was incorporated into an automated scanner. This scanner rotates the directed MsT for data collection at regular intervals. Coupling of the transducer to the plate is accomplished using a shear wave couplant. The array of data that is received is used for compiling B-scans and imaging, utilizing a synthetic aperture focusing algorithm (SAFT). The performance of the probe was evaluated on a 0.5-inch thick carbon steel plate mockup with a surface area of over 100 square feet. The mockup had a variety of known anomalies representing localized and distributed pitting corrosion, gradual wall thinning, and notches of different depths. Experimental data was also acquired using the new probe on a retired storage tank with known corrosion damage. The performance of the new sensor and its limitations are discussed together with general directions in technology development.

INTRODUCTION

The majority of vessels in processing plants such as refineries, chemical plants, electric power generation plants, or ships are manufactured from large plates welded together. Due to large surface area and access limitations, conducting non-destructive testing of these components is costly and time consuming using conventional inspection techniques such as eddy current testing, magnetic flux leakage, and bulk wave ultrasonic testing. Guided wave testing is an emerging method used to inspect these types of structures because of its capability to inspect comparatively larger areas from a single sensor location. Guided wave sensors for these applications can be either directed (i.e., sound propagates in a single line from the sensor) or omnidirectional (i.e., sound propagates in all directions simultaneously). An omnidirectional guided wave sensor has the advantage of inspecting a larger area without changing the sensor position compared to directional guided wave sensors. It is difficult, however, to determine the location of a detected anomaly when using a single omnidirectional sensor; typically, multiple omnidirectional sensors are used together to inspect plate-like structures to allow broad structure coverage with the ability to locate damage.
Several different research groups have investigated multiple omnidirectional sensor system designs. The majority of them have reported that the probes are based on a sparse array of omnidirectional piezoelectric or electromagnetic acoustic transducer (EMAT) probes utilizing a shear horizontal or Lamb wave modes of guided waves [1-7]. Every sensor in these arrays is designed to send and receive guided waves in all directions. In typical structures, this radiation pattern can cause unwanted reflections from geometric features of the structure under test. The basic testing strategy is to send a guided wave from each of the sensor elements of the array incrementally and receive data from all sensor elements simultaneously. Phase delays introduced in each element, combined with synthetic data processing, is used to produce an image of the structure’s condition.

An alternative concept for an omnidirectional sensor system will be discussed in the paper. The probe creates a guided wave propagating in a single predominant direction that covers the area determined by the probe’s beam characteristics. Omnidirectional coverage is accomplished by spinning the probe and acquiring data at predetermined radial positions. In this case, a test structure is predominantly treated as a one directional waveguide, and a minimal number of spurious signals are generated. The rotational process of the probe is supported by a servo motor with high encoder resolution (1 to 5 degree angular increment is typically used for field tests).

The major goals that were targeted are:

- Longer inspection range (5+ meters propagation),
- Omnidirectional probe using SH0 mode with target area of coverage about 100 m²,
- Operating frequencies should be in the range 20 – 500 kHz for broad plate thickness applicability,
- Sensor system operations were accomplished by using an existing single channel instrument for simplicity, and
- Target signal to noise ratio (SNR) of 32 – 46 dB depending on the range of coverage and size of the probe.

Probe rotation requires addressing issues with durability and probe acoustic coupling. This research was focused on the evaluation of the combined effect of these factors on the probe performance on the mockups and also during field tests on a retired storage tank.

**MAGNETOSTRICTIVE TRANSDUCERS FOR PLATES**

Magnetostriective plate probes used for this project utilize a soft magnetic alloy for the excitation of transversal vibrations in the ferromagnetic strip that accentuates the magnetostriective effect [8]. The strip was acoustically coupled to the tested structure using a couplant that supports shear waves. Excitation of transversal vibrations in the strip requires two mutually perpendicular magnetic fields to be applied to the strip with one of these fields being time-varying [9, 10]. Figures 1a and b show two implementations of this approach. Figure 1a has a permanent magnetic field that is perpendicular to propagation direction, and Fig. 1b has a permanent magnetic field that is parallel to propagation direction. Approach “a” is more convenient for utilizing meander type coils producing time-varying magnetic fields. In combination with solenoidal coils supporting a permanent magnetic bias, these types of probes can deliver a high SNR and pure SH0 mode generation in a wide frequency range 16 – 250+ kHz [11-13]. A power supply providing a direct current (DC) is needed to energize the solenoidal coil. As an alternative, the strip could be magnetized with a permanent magnet to eliminate the need for a DC power supply. The magnetostriective strip would need to be heat treated in order to maintain high remnant magnetization. This option is not optimal for permanent monitoring application because remnant magnetization is not a reliable source for sustained residual magnetic fields and can be easily altered by externally applied stress-strain forces. Also, for given parameters of electronics, a meander type AC coil increases the impedance rather quickly when a sensor increases in length or with an increase in frequency.

Probes with the configuration shown in Fig. 1b have been previously classified as “reversed Wiedemann effect probes” in application to cylindrical components and were referenced as MsT probes [14-16]. Permanent magnetic biasing and time-varying magnetization directions are reversed compared to the configuration shown in Fig. 1a. The permanent magnetic biasing dimension in this type of probe is relatively short. This means that it is easier to use rare earth magnets to induce consistent bias fields even if the transducer is a few meters in length. The time-varying magnetic field is supported by a solenoidal coil that is very efficient in supporting high magnitude magnetic fields in wide frequency ranges. Compared to the probe configuration “a,” this probe design essentially has lower impedance coil providing the time-varying magnetic field, which allows for the use of simpler electronics, reducing power requirements and increasing signal strength. High probe efficiency in lower frequency range (below 30 kHz) makes it applicable for long range testing of plates with the thickness up to 76 mm using a non-dispersive SH0 mode (frequency-thickness ratio 1.52 for 20 kHz).
Both of these probe types were evaluated to determine which would be best used for this omnidirectional sensor system. The probe type shown in Fig. 1a was tested using a 300×0.1×50 mm FeCo strip bonded to the exterior of 9.5 mm wall duplex scrubber vessel. Test results indicated that over 46 dB SNR (computed as the ratio between reflection from known plate edges and background noise) was achieved up to 18 m distance from the probe. SH0 mode guided wave was used for the test at a 64 kHz center frequency [17].

**FIGURE 1.** Two implementations of magnetostrictive probes: (a) permanent magnetic field is perpendicular to SH0 wave propagation direction and (b) permanent magnetic field is parallel to SH0 wave propagation direction.

Additional tests were conducted using a 240 × 0.1 × 50 mm (10× 0.003 × 2 inch) MsT probe of the type shown in Fig. 1b. For this test, the sensor was coupled to the carbon steel storage tank using a shear wave couplant. The tank had a 9 mm wall and was filled with diesel fuel. Figure 2 shows data acquired from both directions from the probe using 90 kHz (data rectified positive) and 30 kHz (data rectified negative) center frequencies.

**FIGURE 2.** Data acquired from a storage tank using a 240 × 0.1 × 50 mm (10× 0.003 × 2 inch) probe, shown on Fig. 1b, coupled to the wall using a shear wave couplant using 90 kHz (data rectified positive) and 30 kHz (data rectified negative) center frequencies.

The measured SNR from the weld at -7.5 m distance mark in this test was 32 dB. Assuming a weld signal represents a 20% cross-section area (CSA) reflector, this implies that the plate edge reflection should have an SNR 5 times (or 14 dB) higher, or 46 dB. With such SNR, anomaly Q2 at 90 kHz and anomaly Q3 at 30 kHz in this example (rated as 2% CSA anomalies) were clearly detected. The maximum length of coverage during this test was limited by geometry features of the tank (welded stairs at -8 m distance mark and branch piping at 8.2 m distance mark). However, ±10 meters appears to be a viable range. The results of this particular test clearly indicate the advantage of the approach when multiple frequencies are used for the test. For example, indication Q2 can be seen using both frequencies. At the same time, indications Q1, Q3 and Q4 can be seen only at 30 kHz and were completely missed by 90 kHz. This is due most likely because these missed indications are gradual wall thinning (i.e., a defect with gradual thinning to a maximum depth).

Based on the test results reported in [17] and test results shown in Fig. 2, it was concluded that both types of probes (shown in Figs. 1a and b) could be effectively used for long range omnidirectional coverage of large plates.
The choice of which sensor type to use will be determined by the specific requirements of omnidirectional sensors such as for example predominant frequency range or operating conditions.

Integrating a probe into a rotating sensor system on the wall without losing the efficiency of acoustic coupling is a challenge that is described in the next section.

**OMNIDIRECTIONAL PROBE**

Attaching a plate probe on top of a tested structure requires addressing two major problems – maintaining constant acoustic coupling and protecting the probe from wear and tear. Figure 3 shows two predominant probe designs that can address both problems. A probe, shown in Fig. 3a, uses a protective thin-wall metal cap between the probe and the tested structure. There are two layers of shear wave couplant – layer 1 between the probe and the metal cap and layer 2 between the metal cap and the tested structure. Couplant layer 1 allows for attachment of the probe on top of the internal surface of the cap and also provides a high quality acoustic coupling of ultrasonic energy to the tested structure. The metal cap also serves as a shield protecting all the moving parts of the probe. Both types of magnetostrictive probes (shown in Figs. 1a and b) can be used in this design.

The probe shown in Fig. 3b has a round ferromagnetic patch on the bottom of the metal cap. SH0 mode is generated in the patch via the EMAT principle using a spinning meander type of coil. This meander coil is most similar to the type shown in Fig. 1a, but instead of a solenoid providing the bias along the long direction, the bias is provided using a permanent magnet placed on top of the coil. This second type of omnidirectional probe only needs one layer of couplant (layer 1 between meander coil and ferromagnetic patch is not needed). This makes this probe more suitable for testing of components operating at elevated temperature. The weakness of the probe is the limited length (75 to 100 mm or 3 – 4 inches) due to the need to use a long permanent magnet. Also, the selection of material for the ferromagnetic patch is currently limited to nickel because it has isotropic magnetic properties (i.e., orientation of the coil on the strip does not matter) and it is available in wide sheets. Use of materials with higher magnetostriction like alloys of iron cobalt (FeCo) might require special fabrication and heat treatment due to pronounced anisotropy.

**FIGURE 3.** Two predominant types of omnidirectional probes: (a) a probe uses a protective thin-wall metal cap and two layers of couplant; (b) a probe using ferromagnetic patch bonded to a metal cap, a meander coils with a magnet and one layer of shear wave couplant.

A shear wave couplant is typically used for the testing of structures at ambient temperature. Its properties set practical limitations for using the probe in the field. A few brands of shear wave couplant are available on the market with upper temperature limits of about 32° C (90° F). To increase the temperature limits of the couplant, a custom, SwRI-produced formula is used in the probe based on decomposed sugar mixed with water. Using this formulation, the current temperature limit for the ambient temperature probe is 45° C (113° F). The lower temperature limit for the probe is close to 0° C (32° F) and built-in heaters in the probe can be used to maintain consistent temperature and viscosity of couplant at a more applicable level.

Considering high temperature applications, the probe shown in Fig. 3b might be more suitable for surfaces with temperatures up to 300° C (572° F). Coupling layer 2 in this case would be replaced by a high temperature epoxy. Also, a step-by-step motion would be supported by a stepper motor suitable for operation at elevated temperature.

The probe package is shown in Fig. 4 and includes a motion control box, MsSR3030R instrument and the prototype probe (shown in Fig. 4a). This sensor system was named the MsT360. This particular probe has a replaceable 127 mm (5 inches) long MsT (probe type shown in Fig. 3a) with variable spacing between two sensor strips for direction control (shown in Fig. 4b). A protective metal cap is used to hold the shear wave couplant and to protect the spinning parts (shown in Fig. 4c).
Data is acquired automatically once the initial scan parameters are defined. The parameters that can be custom defined in the software are center frequencies (up to three frequencies can be selected), angular increment (0.2 – 5 degrees) and averaging rates (up to 100 waveforms per second). After data acquisition is finished, data can be presented in a B-scan image or synthetic aperture focusing (SAFT) algorithm can be applied to the data.

As an example, Fig. 5 shows the results of testing on a 6.35 mm (0.25 inch) thick carbon steel plate at 300 kHz with one angular degree increment. A B-scan image is shown in Fig. 5a and reflection from boundaries of the plate can be seen clearly with some other indications. After using SAFT processing, some improvement in image quality can be seen (shown in Fig. 5b). This is mainly accomplished due to the effects of signal averaging and smoothing. After SAFT imaging is processed, the software allows for the generation of a report based on indications specified by the operator. The process of reporting includes specifying the noise floor background, and suspect indications are manually identified by the inspector. A report with information pertaining to the X and Y position and relative amplitude for each indication in both linear and logarithmic scales can then be generated.

Accurate processing of each anomaly’s position is accomplished through analysis software developed for the MsT360 sensor, which also includes an option for the calibration of guided wave velocity and calibration of a zero offset parameter related to the dead zone of the probe. Detection adjustment of thresholds can be done through a selection of colors via a color pallet.
PROBE TESTING ON MOCKUP

The system shown in Fig. 4 was tested on a number of mockups with the wall thickness ranging from 6.3 mm to 12.7 mm (0.25 to 0.5 inches) and in frequency range of 30 – 300 kHz. The most exhaustive tests were performed on a 12.7 mm (0.25 inches) carbon steel mockup with dimensions 3.9 x 2.45 m. A total of 24 anomalies were introduced to the mockup. Figure 6a shows location of anomalies on mockup and pictures of each anomaly are shown in Fig. 6b.

**FIGURE 6.** Mockup test: (a) location of anomalies on mockup; (b) pictures of each anomaly.

The main objective of these tests was the evaluation of the probe performance for detection of different types of anomalies such as notches of different depth and angles relative to the propagation direction, flat bottom and cone bottom drill holes, and graduate wall thinning. Detailed description of each anomaly is presented in Table 1.

**TABLE 1.** Description of anomalies introduced into a mockup plate

<table>
<thead>
<tr>
<th>Defect No.</th>
<th>Type of Defect</th>
<th>Dimensions</th>
<th>Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width(mm)</td>
<td>Length(mm)</td>
<td>Depth</td>
</tr>
<tr>
<td>1</td>
<td>Notch</td>
<td>26</td>
<td>6.3 mm (0.25&quot;)</td>
</tr>
<tr>
<td>2</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>3</td>
<td>Notch</td>
<td>26</td>
<td>7.6 mm (0.3&quot;)</td>
</tr>
<tr>
<td>4</td>
<td>Notch</td>
<td>26</td>
<td>1.27 mm (0.05&quot;)</td>
</tr>
<tr>
<td>5</td>
<td>Notch</td>
<td>26</td>
<td>2.7 mm (0.105&quot;)</td>
</tr>
<tr>
<td>6</td>
<td>Cone Drilled Hole</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>Notch</td>
<td>26</td>
<td>3.9 mm (0.155&quot;)</td>
</tr>
<tr>
<td>8</td>
<td>Notch</td>
<td>26</td>
<td>5.0 mm (0.2&quot;)</td>
</tr>
<tr>
<td>9</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>10</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>11</td>
<td>Wall Thinning (Hatch)</td>
<td>102</td>
<td>102</td>
</tr>
<tr>
<td>12</td>
<td>Cone Drilled Hole</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>13</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>14</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>15</td>
<td>Flat Bottom Drilled Hole</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>16</td>
<td>Flat Bottom Drilled Hole</td>
<td>20</td>
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<td>17</td>
<td>Flat Bottom Drilled Hole</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>Cone Drilled Hole</td>
<td>26.5</td>
<td>26.5</td>
</tr>
<tr>
<td>19</td>
<td>Notch</td>
<td>30</td>
<td>2 mm</td>
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<td>20</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
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<tr>
<td>21</td>
<td>Flat Bottom Drilled Holes (Through Hole)</td>
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<td>12.5</td>
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<tr>
<td>22</td>
<td>Cluster of 2 Drilled Holes</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>23</td>
<td>Cone Drilled Hole</td>
<td>26.5</td>
<td>26.5</td>
</tr>
<tr>
<td>24</td>
<td>Flat Bottom Drilled Hole</td>
<td>12.5</td>
<td>12.5</td>
</tr>
</tbody>
</table>
Results of a test conducted using 60 kHz frequency SH0 guided waves from two probe positions are presented in Figs.
7a and b. Data was acquired using a 127 × 0.1 × 25.4 mm (5 × 0.003 × 1 inch) MsT360 probe, shown in Fig. 4 with a
step increment of 2 degrees with an averaging rate of 10. Total data acquisition time for two probe positions was 30
minutes.

FIGURE 7. Results of a test conducted using 60 kHz frequency: (a) from probe position 1; (b) probe position 2.

The following conclusions could be made as a result of this test:

1. Overall SNR was slightly higher than 40 dB (based on a ratio between the plate edge reflection and
background noise), which is lower compared to the SNR provided by longer probes (46 dB). This SNR should
be sufficient for detection of 2% CSA anomalies.
2. Majority of anomalies produced indications with SNR 6 – 20 dB.
3. Anomalies 16, 17 (2 mm deep, 20 and 10 mm diameter 15 % depth flat bottom drill holes) produced
detectable indications on Figs. 7a and b.
4. One clearly missed anomaly at this frequency was anomaly 11 (11 x 4.8 mm patch with gradual wall
thinning). Lower frequency testing (20-30 kHz) is needed to detect this type of flaw.
5. Strong plate edge effect was observed producing mode converted signals (25-35). For example, indication
27 is a mode conversion SH0 to S0 after wave bouncing from the plate edge. Indications 25 and 26 most
likely originated as S0 mode side-lobes. These indications form groups relevant to every plate edge. The
amplitude of S0 side lobes was about 20 dB lower compared to SH0 plate edge reflection.
6. Saturation of anomaly indications located near the plate edges was observed (anomalies 21-24 in Fig. 7a, and
anomaly 21 in Fig. 7b).
7. Anomaly 1 (6.3 mm or 50% deep notch) produced indication in Fig. 7b. At this probe position, the notch was
parallel to the wave propagation direction and should represent a zero cross-section reflector. Principle of
axial notch detection is well understood in pipes. This effect on plates might need further characterization.
8. There are ghost signals related to imperfections in direction control (the suppression of directional signals
were in the order of 16 dB).

It should be noted that on actual structure, it is not likely to have multiple plate edges in proximity of the probe. This
should significantly reduce the number of non-relevant indications observed during testing on these mockups.
PROBE TESTING ON WATER STORAGE TANK

Additional tests were conducted on a retired water storage tank 14.6 m long, 3 m in diameter, a 15.8 mm wall head (round side cap), and a 9.5 mm wall thickness shell. The tank is shown in Fig. 8a. Tank walls had localized pitting corrosion occasionally forming clusters with 5 - 40% wall loss. Majority of clusters of pitting were visually identified from the inside and quantitatively characterized using manual UT from outside surface. An example of UT grids lined up with the areas of corrosion damage is shown in Fig. 8b. A picture of typical corrosion damage from the inside of the tank is shown in Fig. 8b as well. The omnidirectional probe was mounted on the side cap of a storage tank. The probe, shown in Fig. 4 (the same probe that was used for testing on the mockups), was used for this testing. The ambient temperature during the test was 37° C (98° F) with the actual temperature of the metal achieving temperatures close to 45° C (113° F).

The results of the 60 kHz test with 2° increments are shown in Fig. 8d in the form of a B-scan. The test range was judged based on reflections from welds that could be observed up to 5.4 m distance mark (weld 3). A number of indications were found to be relevant to geometry features such as weld 1 and weld 2, top and bottom branch pipes, tank support ring, welded attachment near the probe. The remaining indications were rated as suspects for corrosion. Indications marked as 10%, 16% and 36% wall loss areas well correlated to known corrosion areas marked with grids from a previous UT examination. For example, a measured corrosion profile of grid 14 with wall loss up to 36% is shown in Fig. 8c. Based on UT readings, this area is affected by a generalized type of corrosion about 10 x 8 cm wide. Overall, about 94 m² area was reported from a single probe position, with the most pronounced indications correlating with the results of the visual examination.

CONCLUSIONS

A new concept of guided wave probe for omnidirectional coverage of large plates was investigated. A plate probe utilizing SH0 mode and magnetostrictive transduction was initially evaluated on mockups and storage tank walls providing about 10 m of coverage in each direction with an SNR about 46 dB (based on reflection from known plate edges). The same type of probe but with 50% smaller length was integrated into a rotating motion system in an omnidirectional embodiment. The issues with acoustic coupling of the spinning probe were successfully resolved using a thin metal cap and a shear wave couplant. Testing of the probe on 12.7 mm walled carbon steel mockup at 60
kHz revealed its capability to detect a large variety of anomalies at a distance up to 2 m from the probe and with overall SNR calculated based on reflections from edges of 40 dB.

Testing of the probe on an actual storage tank indicated the capability of the probe to cover about 94 m² of tested structure including 90° bend and a transition from 15.8 mm to 9.5 mm in wall thickness at 60 kHz. Test results provided good correlation with known areas of corrosion damage of the tank through previous UT examinations.

Data acquired at 60 kHz and 300 kHz were presented in this paper, however, the probe can be configured for operation at a wide variety of frequency ranges between 20 – 500 kHz. The current version of the probe is well suited to applications based on guided wave screening. The future advancements of this technology will include reducing the dimensions of the probe to make it more suitable for SHM applications. In addition, the development of a couplant free version of the probe will be investigated for elevated temperature applications.

ACKNOWLEDGMENTS

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