Demagnetization-based axial magnetized magnetostrictive patch transducers for locating defect in small-diameter pipes using the non-axisymmetric guided wave

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Abstract
The propagation of the non-axisymmetric guided wave in the small-diameter pipe is complicated, which makes the circumferential position of the defect difficult to be determined. This article reports on the design of a segmented axially magnetized magnetostrictive patch transducer array for efficient transduction of non-axisymmetric \( L(M,2) \) modes to determine defect’s axial and circumferential positions in the small-diameter pipe. First, the background of the magnetostrictive patch transducer and non-axisymmetric guided wave in the pipe was presented. Moreover, the theoretical background to the influence of the length-to-width ratio of the magnetized rectangular patch on the demagnetizing factors was introduced. Second, the method of the pipe health monitoring using the designed segmented axially magnetized magnetostrictive patch transducer array was proposed. Third, the most suitable multi-belts of the flexible printed coils were chosen to provide the dynamic magnetic field by the comparison experiments. Then the signal amplitudes of the segmented axially magnetized magnetostrictive patch transducer array with different length–width ratios of magnetostrictive materials were compared with each other to prove the principle of demagnetization. Another two magnetostrictive patch transducer arrays employing permanent magnets were compared with the proposed segmented axially magnetized magnetostrictive patch transducer array. The experiments of pipe health monitoring were carried out to prove that the proposed method can realize pipe health monitoring over time. Fourth, the defect orientation experiments in a 304 stainless steel pipe with 48 mm inner diameter and 2 mm thickness were performed using the proposed segmented axially magnetized magnetostrictive patch transducer array at 650 kHz. The prediction of the circumferential position of the defects correlated well with the defect’s true location through matching the angular profiles of the experimental results and the modulated numerical analysis for several axial distances. The experimental results for the segmented axially magnetized magnetostrictive patch transducer array demonstrated that the proposed segmented axially magnetized magnetostrictive patch transducer array could potentially be applied to detect the axial and circumferential positions of the defect in a small-diameter pipe.

Keywords
Defect detection, non-axisymmetric guided wave, demagnetization, magnetostrictive patch transducer array, structural health monitoring

Introduction
Magnetostrictive patch transducer (MPT) is a kind of electromagnetic acoustic transducer (EMAT)\(^1,2\) that has been widely used in plate and pipe tests.\(^3,4\) Given that the energy of the axisymmetric modes is evenly distributed around the circumference of the pipe,\(^5,6\) the circumferential position of the defect cannot be obtained through the use of axisymmetric modes.\(^8,9\) To
determine the circumferential position of the defect in the pipe, the MPTs that generate the axisymmetric guided wave modes were separated and then used to excite the non-axisymmetric modes by triggering parts of the segmented transducers. Liu et al. applied a modified planar solenoid array coil and a multi-splitting meander coil to an MPT array to trigger axisymmetric mode $T(0,1)$ and $L(0,2)$ for pipe inspection. Kim et al. developed a kind of MPT that could trigger 500 kHz non-axisymmetric $T(M,1)$ to identify the circumferential position of a defect. They subsequently studied in detail the propagation of the non-axisymmetric $T(M,1)$ using the proposed array. However, the non-axisymmetric $L(M,2)$ guided wave modes induced by the MPT array were seldom studied. The objective of this study is to develop a pipe health monitoring system employing MPT array as shown in Figure 1, which can be used to determine the defect’s axial and circumferential positions in small-diameter pipes using non-axisymmetric guided wave $L(M,2)$.

Figure 2 shows the dispersion curves of the stainless steel pipe with 48 mm inner diameter and 2 mm thickness. The modes in red color and blue color are longitudinal and torsional guided wave modes, separately. Different types of guided wave modes have their own characteristics, for example, $L(0,2)$ was proved to have low attenuation during propagation in a concrete-covered pipe comparing with $T(0,1)$. However, the characteristics of the $L(M,2)$ and $T(M,1)$ modes are seldom reported. Design of the highly efficient transducers with the $L(M,2)$ and $T(M,1)$ modes is the first step to study the characteristics of the $T(M,1)$ and $L(M,2)$ modes. Generally, the magnetostrictive patch in the MPT is circumferentially pasted around the cylindrical structure, which is easy to be circumferentially magnetized and provide the circumferential static magnetic field. The circumferential static magnetic field is used to combine with the axial dynamic magnetic field to excite the torsional guided wave modes in the cylindrical structure. The axisymmetric guided wave mode $T(0,1)$ and the non-axisymmetric guided wave modes $T(M,1)$ were studied through the traditional MPT. When the magnetostrictive patch is axially pasted on the cylindrical structure, it is easier to be axially magnetized and used to combine with the axial dynamic magnetic field to excite the longitudinal guided wave modes, which is seldom reported.

Non-axisymmetric guided waves were used to achieve two-dimensional imaging of the defects in pipes. Hayashi and Murase performed defect imaging of a low-frequency $T(0,1)$ mode through time-reversed technology in an aluminum pipe of 111 mm outer diameter and 3.5 mm wall thickness. Dehghan-Niri and Salamone used a multi-helical ultrasonic imaging approach to monitor the structural health of cylindrical structures. Wang et al. proposed a sparse sensor network topologized for cylindrical wave–based identification of damage in large-diameter pipeline structures. However, due to the difference in phase velocity of each mode in one non-axisymmetric guided wave group, the angular profile of the non-axisymmetric guided wave will change after propagating a certain distance. Moreover, the propagation of the non-axisymmetric guided wave in a small-diameter pipe is much more complicated than that of the large-diameter one, which cannot be treated as Lamb wave. The smaller the diameter of the pipe, the faster the angular profile of the non-axisymmetric guided wave change. The fast changing of the angular profile makes the determination of the circumferential position of the defect more difficult in small-diameter pipes than that in large-diameter pipes. Moreover, the helical paths of the guided wave in the pipes make it more difficult to analyze. Owing to the complex angular profile
of non-axisymmetric guided waves in pipes, some researchers have used phase or time control technology to focus the non-axisymmetric mode. In general, designing a kind of array that can simplify the propagation of the non-axisymmetric mode in small-diameter pipes is important in pipe health monitoring. It also occupies the critical position in phase or time control equipment.

Because the difference of the phase velocity between each mode of one non-axisymmetric guided wave group is not critical in a high frequency range as shown in Figure 2(a), exciting the high-frequency signal is a good choice to simplify the propagation of the non-axisymmetric guided wave. However, the higher the frequency, the greater the attenuation of the non-axisymmetric guided wave during propagation. The MPT offers high efficiency, low cost effectiveness, and good controllability of the wavelength, which attract many researchers’ attention. Kim and colleagues proposed several ways to enhance the performance of the torsional-based MPT using the yokes in different shapes and solenoid coils. Zhang et al. proposed a helical comb MPT for inspecting spiral welded pipes using flexural guided waves. Vinogradov et al. designed the broadband magnetostrictive actuators. As the key part of MPT, the patches were circumferentially pasted and magnetized in previous designs. When the magnetostrictive patch is axially magnetized as shown in Figure 3(a), the longitudinal guided wave would be generated efficiently. Based on the principle of demagnetization, the intensity of the magnetic field and the amplitude of the guided wave signal excited by the axially magnetized magnetostrictive patch can be improved by selecting a proper length–width ratio of the magnetostrictive patch. The signal amplitude of the high-frequency non-axisymmetric guided wave can also be improved using the segmented axially magnetized magnetostrictive patch transducer (SAM-MPT) as shown in Figure 3(b).

In this research work, a SAM-MPT array for the efficient transduction of the non-axisymmetric $L(M,2)$ modes into a pipe was proposed. Its main purpose is to determine the axial and circumferential positions of the defects in a 48-mm-inner-diameter, 2-mm-thick 304 stainless steel pipe. First, the principle of demagnetization was introduced to lay the foundation for improvement of the transduction efficiency of the SAM-MPT array. Second, the pipe health monitoring method using the designed SAM-MPT array was proposed. And the theory of the normal mode expansion (NME)
method was introduced to analyze the propagation of the non-axisymmetric \( L(M,2) \) modes in the pipe. Then some comparison experiments were carried out to optimize the proposed SAM-MPT array. Moreover, the signals of the SAM-MPT array were monitored to prove that the proposed SAM-MPT array can be applied in pipe health monitoring over time. The experiments of locating cracks in the pipe were carried out to verify the proposed pipe health monitoring method. The pipe used for experiments was a 304 stainless steel pipe that had an inner diameter of 48 mm and a thickness of 2 mm. Non-axisymmetric \( L(M,2) \) modes at 650 kHz were excited by the six elements of the SAM-MPT array. Finally, the levels of errors between the modulated numerical analysis and measured amplitudes were analyzed and the limitations of the proposed method were discussed. The fewer elements of the SAM-MPT array were proved to have stronger natural beam focusing of the non-axisymmetric \( L(M,2) \) guided wave modes. Each element covered more circumferential areas in the SAM-MPT array. The scope for further development is stated based on the limitation of the proposed method.

The remainder of the article is organized as follows. Section “Theory of demagnetization” describes the theory of the transducer design. The pipe health monitoring method is outlined in section “Configuration of the SAM-MPT array and the pipe health monitoring method.” In section “SAM-MPT array,” some comparison experiments are carried out to optimize the proposed SAM-MPT array. Then the pipe health monitoring experiments are carried out over time. In section “Defect detection in a small-diameter pipe,” the defect detections in 304 stainless steel pipes with 48 mm inner diameter and 2 mm thickness are performed using the proposed SAM-MPT array. Section “Discussion” analyzes the experimental errors and discusses some methods for improving the proposed pipe health monitoring method. The conclusions are summarized in section “Conclusion.”

**Theory of demagnetization**

The principle underlying MPT is the fact that a magnetostrictive material produces normal strain or shear strain when the static and dynamic magnetic fields are applied simultaneously to the magnetostrictive material based on the Joule or Joule and Wiedemann effect. Then the normal strain or shear strain is transferred to the tested sample through the tight coupling between the magnetostrictive material and the tested sample. The greater the magnetostriction, the higher the signal amplitude. The magnetic field intensity of the magnetostrictive material and its magnetostriction are closely related. The study of the magnetic field in the magnetostrictive material plays an important role.

Suppose that a square strip sample is magnetized as shown in Figure 4(a). The magnetic induction lines radiating out from the North Pole and ending at the South Pole constitute a field both outside and inside the square strip. The magnetic induction lines inside the square strip tend to demagnetize it. The self-demagnetizing action of a magnetized body strongly influences the behavior of magnetic materials. Together with the demagnetizing field \( H_d \), there exist another two magnetic fields within the magnetized square strip sample, namely, the magnetization \( M \) and the flux density \( B \) after having been magnetized. The relationship between these three magnetic fields is as follows

\[
B = M - H_d
\]

The magnetization \( M \) is determined by the susceptibility \( \chi \), which is proportional to the applied field \( H \). The flux density \( B \) is directly related to magnetostriction. To maximize the flux density \( B \), the demagnetizing field \( H_d \) should be minimized. The demagnetizing field \( H_d \) of the sample is proportional to the magnetization \( M \) which creates it

\[
H_d = N_d M
\]

where \( N_d \) is the demagnetizing factor. The value of \( N_d \) depends mainly on the shape of the sample, which is not a constant. Applying equation (2) to equation (1) and combining the terms give

\[
B = (1 - N_d) M
\]

The flux density \( B \) increases when the demagnetizing factor \( N_d \) decreases as shown in equation (3). Normally,
Table 1. Fluxmetric and magnetometric demagnetizing factors $N_f$ and $N_m$ of a square bar with dimensions $(2a \times 2b \times 2c)$ magnetized along a dimension (coefficients were multiplied by $10^5$).

<table>
<thead>
<tr>
<th>$\chi$</th>
<th>$\frac{a}{b} = 0.1$</th>
<th>$\frac{a}{b} = 0.3$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi = -1$</td>
<td>83.651/83.973</td>
<td>63.124/65.710</td>
<td>26.132/38.967</td>
<td>8434.7/25.091</td>
<td>3974.2/18.588</td>
<td>1687.5/12.262</td>
</tr>
<tr>
<td>0</td>
<td>79.331/80.500</td>
<td>58.025/61.244</td>
<td>25.873/33.333</td>
<td>11.089/19.831</td>
<td>5864.2/14.036</td>
<td>2363.2/8831.4</td>
</tr>
<tr>
<td>1.5</td>
<td>77.297/788.19</td>
<td>55.513/58.821</td>
<td>25.426/31.030</td>
<td>11.959/17.937</td>
<td>6793.7/12.421</td>
<td>2902.1/7589.8</td>
</tr>
<tr>
<td>9</td>
<td>75.089/76.898</td>
<td>52.760/56.025</td>
<td>24.725/28.713</td>
<td>12.651/16.200</td>
<td>7809.9/10.941</td>
<td>3805/6376.6</td>
</tr>
<tr>
<td>$\infty$</td>
<td>73.843/75.772</td>
<td>51.176/54.367</td>
<td>24.222/27.445</td>
<td>12.928/15.329</td>
<td>8372.7/10.201</td>
<td>4531.6/5705.3</td>
</tr>
</tbody>
</table>

Figure 5. Relationships between the demagnetizing factors and the length–width ratio: (a) fluxmetric factor $N_f$, (b) magnetometric factor $N_m$, (c) derivative of the fluxmetric factor $dN_f/d(\alpha/b)$, and (d) derivative of the magnetometric factor $dN_m/d(\alpha/b)$.

Two demagnetizing factors are defined and used, namely, the fluxmetric factor $N_f$ and the magnetometric factor $N_m$, which depend on the way the magnetization is measured. The values of $N_f$ and $N_m$ for rectangular prisms are given by Chen and colleagues. $^{31-35}$ The calculation model $^{36}$ is a rectangular prism as shown in Figure 3(b). These two kinds of demagnetizing factors can be calculated from either $M_{mid,vol}$ or $H_{d,mid,vol}$ together with the constant susceptibility $\chi$ using

$$N_{f,m} = \frac{H_a}{M_{mid,vol}} - \frac{1}{\chi}$$  \hspace{1cm} (4)$$

$$N_{f,m} = \frac{-H_{d,mid,vol}}{\chi(H_{d,mid,vol} - H_a)}$$  \hspace{1cm} (5)$$

where the subscripts “mid” and “vol” stand for the average over the midplane and over the entire volume, respectively. $H_a$ is the uniform applied field. $H_{d,mid,vol}$ may be calculated from the sum of the prism–midplane and prism–volume averaged fields generated by all rectangular elements. The relationships between $N_f$, $N_m$, and $\alpha/b$ under different susceptibility $\chi$ are tabulated in Table 1 and shown in Figure 5.

Figure 5 shows the relationships between $N_f$, $N_m$, $dN_f/d(\alpha/b)$, $dN_m/d(\alpha/b)$ and the length–width ratio $\alpha/b$. The $dN_f/d(\alpha/b)$ and $dN_m/d(\alpha/b)$ represent the changing rates of $N_f$ and $N_m$ per unit length–width ratio, which are calculated through $(N_{f,m}(i + 1) - N_{f,m}(i))/(\alpha/b(i + 1) - \alpha/b(i))$. $N_f$ and $N_m$ are decreasing when the...
length–width ratio is increasing as shown in Figure 5(a) and (b). Then the demagnetizing field will be smaller according to equation (2), and the flux density $B$ will be greater according to equation (3). It can be seen from Figure 5(c) and (d) that when the length–width ratio is increasing, $dN_f/d(a/b)$ and $dN_m/d(a/b)$ decrease. The relationships between $N_f$, $N_m$, $dN_f/d(a/b)$, $dN_m/d(a/b)$, and the length–width ratio $a/b$ show that the larger the length–width ratio of the magnetized rectangular patch, the smaller the demagnetizing factors and the greater the magnetic field intensity. However, the effect of demagnetization will decrease after the length–width ratio of the magnetized patches has increased to a specific value.

**Configuration of the SAM-MPT array and the pipe health monitoring method**

In this section, the configuration and working principle of the proposed SAM-MPT array are described and the pipe health monitoring method was outlined using the proposed SAM-MPT array. Moreover, section “The NME method” explains the NME method that can simulate the propagation of the non-axisymmetric guided wave in the pipe.

**The pipe health monitoring method**

Figure 1(a) and (b) shows the configuration and working principle of the SAM-MPT array. The 0.15-mm-thick iron cobalt patch (Hiperco 50HS) and a multiple-belt coil constitute the SAM-MPT array as illustrated in Figure 1(a). The iron cobalt patch is a kind of magnetostrictive material. Figure 1(b) shows the principle of the SAM-MPT array generating the non-axisymmetric $L(M,2)$ modes based on the Joule effect in a pipe.

The procedures of the pipe health monitoring method using the proposed SAM-MPT array are as follows: First, three sheets of the iron cobalt patches are fully wrapped around the inspected pipe with epoxy resin to provide the axial static magnetic field as shown in step 1 of Figure 6. The length and the width of the iron cobalt patch are 100 mm and 50 mm, respectively. Second, three sheets of the iron cobalt patches are axially magnetized through a permanent magnet as shown in step 2 of Figure 6. To guarantee the precision of the circumferential orientation of the crack and the good natural beam focusing of the non-axisymmetric guided wave, the six elements of the SAM-MPT array are evenly mounted around the 304 stainless steel pipe. In order to simplify the method of determining the circumferential position of the defect, the six elements of the SAM-MPT array are treated as points. The six circumferential positions represent the circumferential positions of $0^\circ$, $60^\circ$, $120^\circ$, $180^\circ$, $240^\circ$, and $300^\circ$ herein-after. The six thin films of flexible printed circuits (FPCs) that consist of multiple belts are evenly spaced around the sheet of the magnetostrictive material and used to generate the alternating axial dynamic magnetic field as shown in step 3 of Figure 6. Because the static
and dynamic magnetic fields are parallel to each other, the distribution of normal strain is induced in the magnetostrictive material via the Joule effect and exerted to the tested sample through the mechanical coupling. The desired non-axisymmetric \( L(M,2) \)  modes are excited and propagate along the inspected pipe. The center frequency of the excited non-axisymmetric guided wave modes depends on the distance between the adjacent belts. The magnetostrictive patches can be re-magnetized until all the signal amplitudes of the six elements of the SAM-MPT are close.

When the defect is occurring in the pipe over time, there will be new echoes appearing in the signals recorded by the elements of the SAM-MPT array as shown in step 4 of Figure 6. The axial distance of the defect \( L \) can be calculated by the corresponding time of the new echo \( t \) and the group velocity of the non-axisymmetric \( L(M,2) \) modes as shown in Figure 2(b). Because the propagation of the non-axisymmetric \( L(M,2) \) modes is complicated, it should be analyzed by the NME method to explain the experimental results. The NME method is introduced in the next section. In order to simplify the method of determining the circumferential position of the defect, the defect is treated as a point. Assume that the non-axisymmetric \( L(M,2) \) modes are triggered by the element of the SAM-MPT array in \( 300^\circ \). The angular profile of the non-axisymmetric \( L(M,2) \) modes after they propagate a certain distance is shown as a green dotted box in Figure 6, which presents its circumferential energy distribution. The energy of the non-axisymmetric \( L(M,2) \) modes in the red part of the angular profile would be reflected back from the defect. The modulated angular profile of the reflected non-axisymmetric \( L(M,2) \) modes is shown as a red box in Figure 6. Note that the circumferential position with higher energy of the non-axisymmetric guided wave leads to a larger amplitude of the reflected defect echo. The modulated angular profile of the reflected non-axisymmetric \( L(M,2) \) modes is modulated according to the normalized values of the purple points in the six circumferential positions. For example, the modulated angular profile of the reflected non-axisymmetric \( L(M,2) \) modes at \( 300^\circ \) equals to the original angular profile multiplied by 0.7. The red circular points are normalized according to the maximal value of the modulated angular profiles in the six circumferential positions. The predicted circumferential position of the defect aligns to the \( 0^\circ \) of the angular profile when the experimental angular profile of the reflected defect echoes matches that of the modulated numerical analysis. Moreover, given that the angular profile of the non-axisymmetric \( L(M,2) \) guided wave modes is axisymmetric according to a center axis, its characteristic can be used to help determine the circumferential position of the defect.

The angular profile of the non-axisymmetric guided wave in a special axial position can be evaluated by the NME method. The next section illustrates the theory of the NME.

**The NME method**

To determine the axial and circumferential positions of the defects in small-diameter pipes using the non-axisymmetric guided wave, the propagation of the acoustic field generated by the source is needed to be investigated first.

NME\(^{37-42}\) is an effective method to analyze the propagation of the non-axisymmetric guided wave. The final particle velocity field of the cylinder can be expanded in the form of an infinite series of the normal modes traveling in a waveguide, which are orthogonal to each other. The particle velocity field can be written as

\[
v(r, \theta) e^{i(wt-kz)} = \sum_{M,n} A_M^N(z) v_n^M(r, \theta) e^{iwt} \tag{6}\]

where \( w \) and \( k \) are the angular frequency and the wave number, respectively. \( A_M^N(z) \) is the amplitude of NME. \( v_n^M(r, \theta) \) is the velocity field of the \( n \)th mode of \( M \)th circumferential order under a given frequency, which can be written as

\[
v_n^M(r, \theta) = \sum_{\alpha = r, \theta, z} A_n^M R_n^\alpha(r) \Theta_n^M(M\theta) e_\alpha \tag{7}\]

The terms \( R_n^\alpha(r) \) and \( \Theta_n^M(M\theta) \) are the radial components consisting of the Bessel and the modified Bessel functions and the angular component consists of the sinusoidal functions of the particle velocity, which are radial and angular components of the particle velocity, respectively. The NME amplitude can be written as

\[
A_n^M(z) = \frac{e^{-i\frac{MN}{2}z}}{4PM_{nn}} \int_c e^{ik_n^M \eta} \times \left[ \int_{\partial D} \left( v_n^M(T \cdot n_1) ds + \int_{\partial D} v_n^M(T \cdot n_2) ds \right) d\eta \right] \tag{8}\]

The scalar \( P_{nm}^{MN} \) is defined as

\[
P_{nm}^{MN} = -\frac{1}{4} \int_D \left( v_n^M \cdot T_n^{\alpha} + v^\alpha_n \cdot T_n^{M\alpha} \right) e_\alpha d\sigma \tag{9}\]

The term \( T_n^{M\alpha} \) is the stress field and \( P_{nn}^{MN} = 0 \), unless \( M = N \). According to the proposed transducer as shown in Figure 1(b), the axial direction traction is loaded onto the outer boundary of the hollow elastic
cylindrical structure. The loading conditions can be described as follows

\[ T \cdot n_1 = 0 \]  
\[ T \cdot n_1 = \begin{cases} 0, & |z| < L, r = b, \theta < |\theta_0| \\ -p_1(\theta)p_2(z)e_z, & |z| = L, r = b, \theta > |\theta_0| \end{cases} \]  

Substituting equations (10) and (11) into equation (8) gives

\[ A_n^M(z) = \frac{R_{nm}^M(b)}{4P_{nm}} \left( \Theta_r^M, p_1(\theta) \right) \left( p_1(z), e^{i\kappa_n^M z} \right) \]  

where \( \left( \Theta_r^M, p_1(\theta) \right) \) and \( \left( p_1(z), e^{i\kappa_n^M z} \right) \) are the circumferential and axial amplitude factors, respectively, which can be obtained as follows

\[ \left( \Theta_r^M, p_1(\theta) \right) = \begin{cases} \frac{2b}{2b_1(\theta)\sin[(\alpha/2)M]}, & M = 0 \\ \frac{1}{2b_1(\theta)\sin[(\alpha/2)M]}, & M \geq 1 \end{cases} \]  

\[ \left( p_1(z), e^{i\kappa_n^M z} \right) = \frac{2p_2(\theta) \sin(k_n^ML)}{k_n^M} \]  

The NME method is used to simulate the propagation of the non-axisymmetric guided wave induced by the proposed SAM-MPT array in the pipe in the following sections. The simulation results can be used to predict the circumferential position of the defect in the pipe through comparing its angular profiles and the experimental angular profiles.

**SAM-MPT array**

The purpose of this section is to determine the frequency of the non-axisymmetric guided wave modes \( L(M,2) \) and study the effect of the length–width ratio of the axially magnetized magnetostrictive patch on the signal amplitude of the SAM-MPT array. Moreover, the SAM-MPT array is compared with the other two MPT arrays which employed permanent magnets. Then, to prove that the proposed SAM-MPT array can be applied in pipe health monitoring over time, the signals of the SAM-MPT array were monitored.

**Excitation frequency of the SAM-MPT array**

To trigger a frequency of the \( L(M,2) \) modes as high as possible, three different multiple sections of flexible printed circuits (FPCs) that provide dynamic magnetic fields are compared to each other to choose the best type of FPC. The three different FPCs are named \( d_1, d_2, \) and \( d_3 \) FPC for short. Given that the FPC43 can fit pipes of different diameters, it is used to produce the dynamic magnetic field. The belt widths of the \( d_1, d_2, \) and \( d_3 \) FPCs are 5, 4, and 3 mm, and they comprise 10, 12, and 16 sections, respectively. The FPCs are designed long enough to fit different pipe diameters. The axially magnetized iron cobalt patches are the same in the three transducers. The center frequencies \( f_0 \) of the three transducers that employ \( d_1, d_2, \) and \( d_3 \) FPCs are roughly 550, 650, and 800 kHz, respectively, according to equation (15) and Figure 2(a).
\[ f_0 = \frac{V_p}{\lambda} = \frac{V_p}{2d} \]  

(15)

where \( \lambda \) is the wavelength, \( V_p \) is the phase velocity, and \( f_0 \) is the center frequency of the excited guided wave (GW) mode. The frequency responses of the three FPCs are plotted in Figure 7. Each of the six FPC elements is wrapped around the iron cobalt patch. Hence, each FPC covers one sixth of the perimeter of the pipe. The observed center frequencies of the three transducers are roughly the same as that calculated from equation (15). The three frequency-sweeping experiments show that the higher the center frequency, the weaker the guided wave signal. The three signals listed on the right-hand side of Figure 7 are the peak points of the three frequency sweepings. The signal amplitude of the transducer that employs \( d_3 \) FPC is not strong enough and is not sensitive to the defect.

Figure 8 shows the frequency spectra of the non-axisymmetric \( L(M,2) \) modes at 650 kHz excited by the transducers that employed the \( d_1 \) and \( d_2 \) FPCs. Due to the center frequency of the \( d_1 \) FPC was set at 580 kHz, a large quantity of guided wave energy in the frequency range 580–600 kHz as shown in Figure 8(a), while the frequency spectrum triggered using the \( d_2 \) FPC shows a more focusing guided wave energy at the frequency range from 620 to 670 kHz. Because the wide-frequency signal provided by the \( d_1 \) FPC may affect the received guided wave signal in broadband, making the signal very difficult to analyze; therefore, the \( d_2 \) FPC was employed to implement the desired SAM-MPT to trigger the purer 650-kHz signals.

**Length–width ratio of the axially magnetized magnetostrictive patch**

The axially magnetized iron cobalt patch is used to supply the static magnetic field because iron cobalt shows a good magnetostrictive effect. As the critical part in the SAM-MPT, the magnetized iron cobalt patch has a great influence on its magnetic field intensity and signal amplitude. The principle of demagnetization demonstrates that the length–width ratio of the magnetized magnetostrictive material occupies an important position in the improvement of the magnetic field’s intensity.

To prove the principle of the demagnetization presented in section of the “Theory of demagnetizing”, the non-axisymmetric \( L(M,2) \) modes of four different SAM-MPT arrays were recorded to compare with one another. The length–width ratios of the iron cobalt patches in the four different SAM-MPT arrays are set at 1:3, 1:1, 2:1, and 3:1, respectively. The 304 stainless steel pipes with 48 mm inner diameter, 2 mm wall thickness, and 500 mm length were chosen as the testing samples. The first SAM-MPT array had its patch wrapped around a pipe as shown in Figure 9(a). Figure 9(b) to (d) shows the other three SAM-MPT arrays with their patches at different length–width ratios, which were pasted axially around the pipe. The length \( a \) and the width \( b \) shown in Figure 9 correspond to \( a \) and \( b \) shown in Figure 4(b). The iron cobalt patches were axially magnetized to provide static magnetic fields. The dynamic magnetic fields were produced by the same kind of FPC in these four experiments. The excitation frequency was 650 kHz and the experimental results are shown in Figure 9.

Figure 9(a) to (d) illustrates the non-axisymmetric guided wave signals of the four different SAM-MPT arrays. Apart from the \( L(M,2) \) modes, there exist \( T(M,1) \) modes in Figure 9(a) through the relationship between the pipe length and the time difference (\( \Delta t \)) between the two peak values of the first end echo and the trigger waveforms. The signal amplitude of the \( T(M,1) \) modes drops substantially when the length–width ratio changes from 1:3 to 1:1 as shown in
Figure 9(b). Moreover, it can be seen from Figure 9(c) that the signal–noise ratio improves significantly and the $\text{T}(M,1)$ modes continue to be suppressed when the length–width ratio changes to 2:1. Because the effect of the magnetostrictive material’s length–width ratio on the demagnetizing factor is limited after it has exceeded 2 as shown in Figure 5(c) and (d), the signal in Figure 9(d) does not improve significantly when compared with that in Figure 9(c). Furthermore, the contact between the magnetostrictive material and the tested pipe sample caused attenuation to the guided wave during propagation. That is the reason why the amplitudes of the multiple echoes decrease faster than the others as illustrated in Figure 9(d).

Table 2 summarizes the relationships between the propagation distances of the non-axisymmetric $\text{L}(M,2)$ and the length–width ratios of the iron cobalt patches set at (a) $a:b = 0.33$, (b) $a:b = 1$, (c) $a:b = 2$, and (d) $a:b = 3$.

<table>
<thead>
<tr>
<th>$a:b$</th>
<th>Propagation distance of $\text{L}(M,2)$, mm</th>
<th>Propagation distance of $\text{T}(M,1)$, mm</th>
<th>Demagnetizing factor ($\chi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33 (1:3)</td>
<td>2000</td>
<td>1000</td>
<td>N/A</td>
</tr>
<tr>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>39,178/42,639</td>
</tr>
<tr>
<td>0.7</td>
<td>–</td>
<td>–</td>
<td>31,607/35,049</td>
</tr>
<tr>
<td>1 (1:1)</td>
<td>2000</td>
<td>0</td>
<td>24,222/27,445</td>
</tr>
<tr>
<td>1.5</td>
<td>–</td>
<td>–</td>
<td>17,091/19,882</td>
</tr>
<tr>
<td>2 (2:1)</td>
<td>2500</td>
<td>0</td>
<td>12,651/16,200</td>
</tr>
<tr>
<td>4 (4:1)</td>
<td>2500</td>
<td>0</td>
<td>–</td>
</tr>
</tbody>
</table>

Fang and Tse
distances of the $L(M,2)$ and $T(M,1)$ modes may be farther than that shown in Table 2, because the propagation distances are not in the multiple of 500 mm in practice. The experimental results show that when the length–width ratio $a:b$ is increasing, the demagnetizing factor is decreasing and the axial magnetic field intensity is increasing. Hence, the signal amplitudes of the $L(M,2)$ modes become greater and the signal amplitudes of the $T(M,1)$ modes become weaker. The results obtained from experiments match with those from the numerical analysis.

Comparison between the MPT array employing permanent magnets and the pre-magnetized magnetostrictive material

Because the strength of the static magnetic field provided by the permanent magnets is greater than that of the pre-magnetized magnetostrictive materials, most of the MPTs contain permanent magnets. To produce the expansion and compression stress in the tested cylindrical structure in the MPTs employed with permanent magnets, the permanent magnets should provide the axial static magnetic fields. Figures 10 and 11 show two kinds of MPT array employing permanent magnets. The cubical permanent magnet in Figure 10 is magnetized along the length direction, the length $\times$ width $\times$ thickness of which is 30 mm $\times$ 10 mm $\times$ 3 mm. The arc permanent magnet in Figure 11 is magnetized along the width direction, the outer radius $\times$ inner radius $\times$ width $\times$ angle of which is 28 mm $\times$ 18 mm $\times$ 5 mm $\times$ 70°. The poles of the adjacent magnets are opposite as shown in Figure 11. The magnetic arrays can stay stable around the pipe because of the attraction of the opposite poles. The tested pipe is the 304 stainless steel pipe with 750 mm length, 48 mm inner diameter, and 2 mm thickness. The width of the MPT arrays is 50 mm. The pipe samples used in Figures 10 and 11 are the same. There exists no defect in the pipe. The MPT arrays are mounted 150 mm away from one end of the pipe as shown in Figures 10 and 11. The standard deviation $\sigma$ is calculated through equation (16) as follows, which is used to evaluate the level of discrepancy of the signal amplitudes

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N} (x_n - \mu)^2}{N}}$$

(16)

where $x_n$ is one of the signal amplitudes, $\mu$ is the average value of all the signal amplitudes, and $N$ is the number of signals. $N$ is equal to 6 because there are six elements in the MPT array. The guided wave signals of the two kinds of the MPT arrays are shown in

Figure 10. Signals of the MPT array employing cubical permanent magnets.
Figures 10 and 11. The end echoes reflected from the left end are submerged in the triggering waveforms. The amplitudes of the right end echoes vary from different circumferential positions of the array as shown in Figures 10 and 11. The amplitudes of the six signals are normalized before calculating the standard deviation for comparison. The normalization procedures are as follows. First, the maximal amplitude of the signal is set at 1, and then the other amplitudes are normalized according to the maximal amplitude. The standard deviations of the signal amplitudes of the MPT arrays employing cubical and arc permanent magnets are 0.091 and 0.100, respectively. The discrepancies of these signals come from many aspects, for example, the magnetic strengths of different magnets, the deviation of the circumferential positions of the magnets, the difference in the contact between each sheet of the magnetostrictive material and the pipe, and so on. Adjusting the positions of permanent magnets can modulate the signal amplitudes. However, moving any one magnet of the MPT array in Figure 11 would affect the other magnets’ positions because the adjacent magnets attract each other. It means that to calibrate the amplitudes of the guided wave signals excited by the MPT array as shown in Figure 11 is difficult. Moreover, it is still not easy for the MPT array as shown in Figure 10. The reason is that the discrepancies of some signals are so great that it is difficult to modulate the amplitudes of all signals to be consistent through adjusting the positions of permanent magnets. For example, the signal amplitude of the No. 1 element is much larger than that of the No. 6 element.

The discrepancies of the signal amplitudes are not so great for the SAM-MPT. All the signal amplitudes can be modulated through multiple magnetization to make them consistent. Moreover, the advantages of using the pre-magnetized magnetostrictive material to provide the static magnetic field are as follows. First, the size of the array can be reduced. Second, the array without the magnet can be easily installed in other pipes that have different diameters. Hence, there is no need to manufacture new permanent magnets of different dimensions. All the aforementioned problems can be avoided using the pre-magnetized magnetostrictive material. To calibrate the amplitudes of the guided wave signals excited by the MPT array as soon as possible, employing both pre-magnetized magnetostrictive material and permanent magnets is another choice at some time.

**Pipe health monitoring over time**

The pipe health monitoring method discussed above has not been proven that can realize pipe health monitoring over time. Figures 12 and 13 show the variance
of the amplitude of the guided wave signals excited by the SAM-MPT array over time. The pipe is the same one tested in section “Comparison between the MPT array employing permanent magnets and pre-magnetized magnetostrictive material.” The SAM-MPT array is mounted 150 mm away from one end of the pipe. The standard deviation of the signal amplitudes of the six elements is 0.041 on the first monitoring day, which is smaller than those of the other MPT arrays employing permanent magnets. The amplitudes of the six signals are normalized before calculating the standard deviation for comparison. The standard deviation $\sigma$ is also used to evaluate the degradation of the amplitude of the non-axisymmetric guided wave signal over time. The $N$ value is equal to 15 because the SAM-MPT array is monitored within 15 days.

The amplitudes of the signals are normalized before calculating the standard deviation for comparison. The standard deviations of the six signal amplitudes’ degradations over time are 0.006, 0.008, 0.009, 0.010, 0.010, and 0.007. The experimental results prove that the degradations of the transducers are not serious within 15 days. Moreover, the signals of the SAM-MPT array will not change a lot only if the pre-magnetized magnetostrictive patches are not affected by other magnetic fields and the contact areas between the FPCs and the pre-magnetized magnetostrictive patches are invariable.

### Defect detection in a small-diameter pipe

#### Experimental setup

Figure 14 shows the experimental setup of the pipe inspection when the SAM-MPT array is used. The setup consists of an Agilent 33250A arbitrary waveform generator, an RPR-4000 high-power ultrasonic measurement system, and a high-sampling-rate
oscilloscope. A five-cycle Hanning window-modulating sine wave was triggered by Agilent 33250A after it had been amplified by RPR-4000. The modulated sine wave was then transformed to the SAM-MPT array in order to excite the desired non-axisymmetric guided wave into the tested pipe. The reflected non-axisymmetric guided wave signals were received by the same SAM-MPT array. The high-sampling-rate oscilloscope was used to record the reflected guided wave signals. Three sheets of the 100 mm $\times$ 50 mm iron cobalt patches were pasted onto the outer surface of the 304 stainless steel pipe with 48 mm inner diameter and 2 mm thickness. Six thin films of FPCs were equably attached around the iron cobalt patches.

**Angular profiles**

The angular profiles of the non-axisymmetric guided wave $L(M,2)$ modes in a stainless steel pipe with 48 mm inner diameter and 2 mm thickness are shown in Figure 15. They are calculated using the NME method described in section “The NME method.” There exist 14 circumferential orders at 650 kHz for the second mode.

The 0° direction represents the direction of the excited $L(M,2)$ modes. Note that the angular profiles of the non-axisymmetric guided wave modes represented the distributed energy of the non-axisymmetric guided wave modes around the pipe. The signal energy is mostly focused at the 0° direction when the $L(M,2)$ modes have propagated to a pipe length of 100 mm as shown in Figure 15(a). After the $L(M,2)$ modes have propagated to 280 mm, the distributed signal energy is shown in Figure 15(b). The signal energy is distrusted in all angular profiles. Figure 15(c) and (d) shows the signal energy distribution of the $L(M,2)$ modes when they have propagated to a pipe length of 320 and 480 mm, respectively. Note that more signal energy occurs in the opposite side (180°) but less energy occurs at the 0° direction. As compared to the energy distribution that occurs as shown in Figure 15(a), the distribution of energy shifts to the side of 180°. Given that the energy of the different circumferential positions distributes unevenly around the pipe, the angular profiles of the non-axisymmetric guided wave modes simulated by the NME method can be used to determine the circumferential position of the defect in pipe through comparing with the angular profiles extracted from the experiments.

**Experimental results**

**Transducer characterization.** Figure 16 shows the orientation of a crack that occurred at a 304 stainless steel pipe with a length of 1750 mm. The SAM-MPT array was mounted 450 mm away from the left end of the pipe. A circumferential defect with length $\times$ depth $\times$ width of 15 mm $\times$ 2 mm $\times$ 1 mm was artificially made on the pipe that was 320 mm away from the SAM-MPT array. This defect was named as the first defect and was aligned with the No. 2 element of the SAM-MPT array as shown in Figure 16. Before the
defect was made, the non-axisymmetric guided wave signals propagating along the intact pipe were recorded as the reference. The blue waveforms were the signals recorded before making the first defect. The red dashed waveforms were the signals recorded after making the first defect.

Figure 17 shows the results obtained after having the second defect in the experiment. The second circumferential defect of length $3\times$ depth $3\times$ width of 19 mm $3\times$ 2 mm $3\times$ 1.2 mm was 280 mm away from the array and was aligned with the No. 4 element of the SAM-MPT array. The blue waveforms were the signals recorded before making the second defect. The red dashed waveforms were the signals recorded after making the second defect.

To further demonstrate the use of the above method, another experiment was conducted. Another 304 stainless steel pipe that had a length of 700 mm was used in the experiment. The SAM-MPT array was mounted 500 mm away from one end of the pipe. An artificial circumferential defect with length $\times$ depth $\times$ width of 21 mm $\times$ 2 mm $\times$ 1.2 mm was created in the pipe, which was 480 mm away from the SAM-MPT array as shown in Figure 18. The defect was aligned with the No. 2 element of the SAM-MPT array. The temporal waveforms of the non-axisymmetric guided wave signals received by each of the six elements are plotted in Figure 18 with the echoes reflected by the defect and the pipe far end. The blue waveforms were the signals recorded before making the only one defect. The red dashed waveforms were the signals recorded after making the only one defect.

Defect non-destructive evaluation using the transducer. Figure 16 shows the results obtained before and after having the first defect in the pipe with 1750 mm in length. After calculating the propagation distance of the $L_{(M,2)}$ modes using its group velocity as shown in Figure 2(b) and the time-of-flight of the echo, it is found that the echo that occurs around 0.18 ms is the $L_{(M,2)}$ mode's reflection generated by the near end of the pipe. The echo of defect occurs around 0.12 ms. The calculated axial position of the defect correlates...
Figure 16. Signals received by the six elements of the SAM-MPT array placed at different orientation around the tested pipe before and after making the first defect.

Figure 17. Signals received by the six elements of the SAM-MPT array placed at different orientation around the tested pipe before and after making the second defect.
well with the actual axial position of the first defect. Given that the circumferential position with the higher energy of the non-axisymmetric guided wave leads to a larger amplitude of the reflected defect echo, the modulated numerical angular profile of the defect echoes shown in Figure 19(b) is modulated according to the normalized values of the original angular profile in the six circumferential positions. The red points in Figure 19(b) are obtained from the six peak values of the red dashed defect echoes in Figure 17, which are normalized according to the maximal value of the modulated numerical angular profiles of the defect echoes in the six circumferential positions. Note that the maximal peak value of the six peak values is equal to that of the modulated numerical angular profiles of the defect echoes. Finally, the predicted circumferential position of the defect aligns to the $0^\circ$ of the modulated angular profile when the angular profile of the reflected defect echo matches that of the modulated numerical results. The circumferential position of the defect is shown as with a red box in Figure 19(b). The black part is the pipe and the gray part is the defect. It can be seen from Figure 19(b) that the defect aligns with the No. 2 element of the SAM-MPT array. The predicted position of the defect correlates well with the true location.

Figure 17 shows the results obtained before and after having the second defect in the pipe with 1750 mm in length. The echoes of the defect occur around 0.11 ms. The calculated axial position correlates well with the actual axial position of the second defect. The modulated numerical angular profile of the defect echoes shown in Figure 19(a) is modulated according to the normalized values of the original angular profile in the six circumferential positions. The red points in Figure 19(a) are obtained from the six peak values of the red dashed defect echoes in Figure 17, which are normalized according to the maximal value of the modulated numerical angular profiles of the defect echoes in the six circumferential positions. Note that the maximal peak value of the six peak values is equal to that of the modulated numerical angular profiles of the defect echoes. Finally, the predicted circumferential position of the defect aligns to the $0^\circ$ of the angular profile when the angular profile of the reflected defect echo matches that of the modulated numerical results. It can be seen from Figure 19(b) that the defect aligns with the No. 4 element of the SAM-MPT array.

Figure 18. Signals received by the six elements of the SAM-MPT array placed at different orientation around the tested pipe before and after making the only one defect.
element of the SAM-MPT array. The estimated position of the defect correlates well with the true location.

Figure 18 shows the results obtained before and after having the only one defect in the pipe with 700 mm in length. After calculating the propagation distance of the $L(M,2)$ modes using its group velocity and the time-of-flight of the echo, it is found that the echo that occurs around 0.23 ms is the $L(M,2)$ mode’s reflection generated by the far end of the pipe. The defect echoes occur around 0.19 ms, and its calculated axial position correlates well with the actual axial position. The experimental angular profile is shown in Figure 19(c) with a length of 480 mm. The modulated numerical angular profile of the defect echoes shown in Figure 19(c) is modulated according to the normalized values of the original angular profile in the six circumferential positions. The red points in Figure 19(c) are obtained from the six peak values of the red dashed defect echoes.

**Figure 19.** Modulated angular profiles of simulations and experiments when the $L(M,2)$ modes propagated to a pipe distance of (a) 280 mm, (b) 320 mm, and (c) 480 mm.
in Figure 18, which are normalized according to the maximal value of the modulated numerical angular profiles of the defect echoes in the six circumferential positions. Note that the maximal peak value of the six peak values is equal to that of the modulated numerical angular profiles of the defect echoes. Finally, the predicted circumferential position of the defect aligns to the $0^\circ$ of the angular profile when the angular profile of the reflected defect echo matches that of the modulated numerical results. It can be seen from Figure 19(c) that the defect aligns with the No. 2 element of the SAM-MPT array. The estimated position of the defect correlates well with the true location. Moreover, if the axis that connected the circumferential position of the defect and its opposite circumferential position is named as the center axis as shown in Figure 19(a) to (c). The amplitudes of the measured data that are axisymmetric according to the center axis are close as shown in Figure 19. They can be used to help determine the circumferential position of the defect. Either the circumferential position of the defect aligns with or is opposite to the element of the SAM-MPT array that has more remarkable defect echo depending on the axial position of the defect as shown in Figure 19. For example, the amplitudes of the defect echoes are close for No.1 and No.3, No.6 and No.4 elements as shown in Figure 19(c). Given that more energy of the non-axisymmetric guided wave $L(M,2)$ modes focuses at the $180^\circ$ direction when the $L(M,2)$ modes have propagated to a pipe length of 480 mm, the element of the SAM-MPT array at the $180^\circ$ direction can obtain more energy of the reflected defect echo. The defect aligns with the No.2 element because the No.5 element has more remarkable defect echo, the same theory for Figure 19(a) and (b).

**Discussion**

*Experimental error analysis and limitations of the proposed method*

The levels of the errors between the modulated numerical and the experimental angular profiles are shown in Table 3. The SAM-MPT array contains six elements. Each element aligns to a special circumferential position. The levels of errors between the modulated numerical and the experimental amplitudes in the six circumferential positions are calculated by equation (17).
Table 3. The discrepancy comes from the distorted direct waves. Because the direct waves are located near to the triggered wave, they have been distorted as shown in the waveforms of the middle diagram of Figure 20. The experiment also proves that fewer elements of the SAM-MPT array may lead to better natural beam focusing of the non-axisymmetric guided wave when the angular profile shown in Figure 20 is compared with that in Figure 15(c). Moreover, the non-axisymmetric guided wave with a higher energy can propagate farther. However, the trade-off is that the accuracy of determining the circumferential orientation of defects will be reduced.

Scope for further development

The proposed SAM-MPT array is proved to be able to simultaneously determine the axial and circumferential positions of the defects in pipes. However, there also exist some problems that need to be solved.

First, as discussed in section “Experimental error analysis and limitations of the proposed method,” the levels of the errors between the modulated numerical and the experimental angular profiles are high for some elements. One way is to improve the pipe health monitoring method, the non-axisymmetric guided wave \( L(M,2) \) modes reflected from different sizes of the defects and received by the elements of the MPT array need to be studied first. Another way is to simplify the propagation of the non-axisymmetric guided wave modes. To apply fewer elements of the SAM-MPT array so that each element can cover more circumferential areas has been proven to work.
also simplify the propagation of the non-axisymmetric guided wave modes.

Second, the transduction efficiency of the SAM-MPT array needs to be improved. It can not only trigger high-frequency non-axisymmetric guided wave modes, but can also be used to test smaller defects or more realistic cracks in the further development. In terms of the dynamic magnetic field, the strength of the dynamic magnetic field only depends on the power of the instrument. However, the ways to improve the strength of the static magnetic field are varied. The strength of the static magnetic field provided by the induced magnetic field is great and controllable through changing the current. The signal amplitudes of all the elements of the MPT array can be tuned to be the same value. However, the structure of the MPT employing the induced magnetic field may be complex, which is also time-consuming to manufacture. To choose a kind of magnetostrictive material with larger magnetostriiction is another choice. However, the material should not be too brittle so that it can be pasted around the cylindrical structure. Moreover, given that there exists the best strength of the static magnetic field that can maximize the signal amplitude of the guided wave as studied in Fang and Tse\textsuperscript{18} and Kim and Kwon\textsuperscript{27} the magnetization curve of the magnetostrictive material deserves further study so that the best strength of the static magnetic field can be determined.

Third, the characteristics of the $T(M,1)$ and $L(M,2)$ modes are seldom reported. The comparison between the $T(M,1)$ and $L(M,2)$ modes needs to be carried out so that the different non-axisymmetric guided wave modes can be applied in their suitable scopes.

**Conclusion**

In this article, we reported a kind of Joule effect–based MPT array with an axially magnetized patch for efficient transduction of non-axisymmetric $L(M,2)$ to determine the defect’s axial and circumferential positions in a small-diameter pipe. The multi-belt FPC and the iron cobalt patches were chosen to provide the dynamic and static magnetic fields separately in the SAM-MPT array. After the frequency sweep experiments of FPCs had been compared with different belt widths, the 4-mm-belt-width FPC that had good frequency control and a strong signal was chosen to trigger 650 kHz non-axisymmetric $L(M,2)$ to carry out defect detection experiments in 304 stainless steel pipes with 48 mm inner diameter and 2 mm thickness. The axially magnetized iron cobalt patch was used to supply the axial static magnetic field, which itself produced the magnetostrictive effect. The theory of demagnetization stated that the greater the length–width ratio of the magnetized rectangular patch, the smaller the demagnetizing factors and the greater the magnetic field intensity. The comparison experiments proved that the greater the length–width ratio of the rectangular patches, the stronger the signal. Moreover, both the demagnetization principles and the experiments demonstrated that the effect of demagnetization was limited when the length–width ratio of the magnetized patches exceeded 2. The signal amplitudes of the proposed SAM-MPT array were proved to be more consistent than the other two MPT arrays that employed permanent magnets. Moreover, the signals of the SAM-MPT array were monitored to prove that the proposed SAM-MPT array can be applied in pipe health monitoring over time.

Experiments were performed by having three artificial cracks introduced to the pipes at different axial crack orientation. The configurations of the tested pipes were the same as before. The SAM-MPT array that had six elements of FPCs was used to excite $L(M,2)$ modes at 650 kHz again. First, the axial locations of defects had been determined using the velocity of the excited non-axisymmetric guided wave $L(M,2)$ modes and the time-of-flight of the defect echo. Second, the predicted circumferential positions of the defects correlated well with the true locations when the angular profiles of the experiments match the modulated angular profiles forecasted by the NME method. The amplitudes of the measured data that were axisymmetric according to the center axis were close. They can also be used to help determine the circumferential position of the defect. Either the circumferential position of the defect aligns with or is opposite to the element of the SAM-MPT array that had greater defect echo depending on the axial position of the defect. In conclusion, the proposed SAM-MPT array can be used to excite non-axisymmetric $L(M,2)$ guided wave modes efficiently. Using the proposed pipe health monitoring method, the axial location and the circumferential orientation of each defect can be determined accurately even if the inspected pipe is small in diameter.

**Declaration of conflicting interests**

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