Magnetostrictive helical array transducer for inspecting spiral welded pipes using flexural guided waves

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https://doi.org/10.1063/1.4974596
Magnetostrictive Helical Array Transducer for Inspecting Spiral Welded Pipes Using Flexural Guided Waves

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Abstract. A wavefront analysis indicates that a flexural wave propagates at a helix angle with respect to the pipe axis. The expression for calculation of the helix angle for each flexural mode is given, and the helix angle dispersion curves for flexural modes are calculated. According to the new understanding of flexural guided waves, a magnetostrictive helical array transducer (MHAT) is proposed for selectively exciting a single predominant flexural torsional guided wave in a pipe and inspecting spiral welded pipes using flexural waves. A MHAT contains a pre-magnetized magnetostrictive patch that is helically coupled with the outer surface of a pipe, and an array of novel compound comb coils that are wrapped around the helical magnetostrictive patch. The proposed wideband MHAT possesses the direction control ability. A verification experiment indicates that flexural torsional mode T(3,1) at center frequency f=64kHz is effectively actuated by a MHAT with 13-degree helix angle. A 20-degree MHAT is adopted to inspect a spiral welded pipe, an artificial notch with cross section loss CSL=2.7% is effectively detected by using flexural waves.

INTRODUCTION

Millions of miles of pipes are being used in both civil and industrial fields. Spiral welded pipes, especially widely distributed in China and Russia, are applied in fields such as drainage, architecture as well as oil and gas storage and transportation. Inspection of spiral welded pipes is a challenging task due to their complex geometry. Ultrasonic guided waves have already been proved to have great potential in on-line non-destructive evaluation and long-term structural health monitoring of pipelines [1, 2]. Axisymmetric torsional and longitudinal wave modes, such as T(0,1) and L(0,2), have been widely applied to detect and locate defects which cause changes in the cross section of a pipe to some extent. However, axisymmetric modes are mainly used for detecting corrosions and transverse notches or cracks in seamless steel pipes. An axisymmetric wave experiences destructive interference when it encounters a spiral weld, as shown in Fig. 1. Therefore, axisymmetric waves have poor detection sensitivity for defects in spiral welded pipes. The application of flexural modes tends to provide enhanced ability to detect defects, especially detection of defects in spiral welded pipes, compared to the use of axisymmetric modes. A flexural wave helix angle can be selected to avoid significant interaction across the spiral weld that could create confusion using axisymmetric waves. A flexural mode can be selected so that the flexural wave oriented parallel to a spiral weld to minimize the weld effect, or a flexural mode can be used to impinge perpendicular on the spiral weld to improve the signal to noise ratio (SNR).

Flexural guided waves in pipes have been known for decades, excitation of flexural guided waves has also been considered in the literature. Gazis [3] had shown that there exists an infinite number of normal modes, including axisymmetric modes and non-axisymmetric modes, in an elastic hollow cylinder, each with its own characteristics such as phase velocity, group velocity and wave structure profile. He obtained the general solution of harmonic waves propagating in an infinite long hollow cylinder, which has been very beneficial for long range guided wave inspection on widely distributed pipelines. The forced response problem in a hollow cylinder problem was first studied by Ditri et al. [4] with Normal Mode Expansion (NME) method to obtain the amplitude factors of different guided wave modes, including axisymmetric and flexural modes. Li et al. [5], Shin et al. [6] studied the excitation and propagation of non-
axisymmetric waves by using Ditri’s method. Angular profile was calculated by taking into account the amplitude factors of every excited mode. Sun et al. [7] studied flexural torsional wave mechanics and focusing by using NME. The Four-Dimensional Tuning Process was implemented to control angular profiles for energy focusing. Li et al [8], Davies et al [9] and Velichko et al. [10] considered a pipe as an unrolled plate to simplify the complex pipe guided wave solution for flexural waves by assuming plate-like behavior based on the approximation that the diameter of the pipe is much larger than the wall thickness. Y. Liu et al. [11] presented a plate ray perspective for elastic wave propagation in hollow circular cylinders. A helical inter-digital transducer was designed for the excitation of a single dominant flexural mode. However, most of current methods for exciting flexural modes suffer from two disadvantages. First, one pure flexural mode cannot be excited. Second, the excited flexural waves cannot cover the entire surface of a pipe. Therefore, excitation of pure flexural waves which cover the entire surface of a pipe is a crucial element for a complete scan of the pipe with flexural guided waves.

FIGURE 1. An axisymmetric wave experiences destructive interference when it encounters a spiral weld.

In this paper, a novel magnetostrictive transducer is proposed for exciting and receiving predominant flexural waves. A wavefront analysis indicates that a flexural wave propagates at a helix angle (HA) with respect to the pipe axis. The expression for calculation of the helix angle for each flexural mode is given. The concept of helix angle dispersion is introduced, and the helix angle dispersion curves for flexural modes are calculated. According to the new understanding of flexural modes in pipes, a helical loading for exciting a dominant flexural mode is proposed and verified by a finite element evaluation. A magnetostrictive Helical Array Transducer (MHAT) is then developed to excite and receive a single predominant flexural torsional wave in a pipe. A verification experiment indicates that flexural torsional mode T(3,1) at center frequency f=64kHz is effectively actuated by a MHAT with 13-degree helix angle. A 20-degree MHAT is adopted to inspect a spiral welded pipe, an artificial notch with cross section loss CSL=2.7% is effectively detected by using flexural waves.

THEORY

Analysis of Flexural Guided Waves

Guided waves in hollow cylinders may travel in circumferential or axial direction [1]. Guided waves propagating in axial direction in hollow cylinders are considered in this article. The guided waves propagating in the axial direction involve torsional waves T(N, m) and longitudinal waves L(N, m), where the integer N denotes the circumferential order and m represents the group order of a mode. The torsional waves have dominant particle motion in the \( \theta \) direction, and the longitudinal waves have dominant particle motion in \( r \) and/or \( z \) direction. Guided waves propagating in the axial direction of hollow cylinders contain axisymmetric modes (N=0) and non-axisymmetric modes (N\#0, also known as flexural modes).

The guided wave behavior in a spiral welded pipe is approximately the same as that in a seamless steel pipe with the same diameter and thickness. Therefore, the guided wave theory in an elastic isotropic traction-free hollow cylinder is adopted here. There exists an infinite number of guided wave modes in a hollow cylinder, each with its own characteristics such as phase velocity, group velocity and wave structure profile. The dispersion relation for a hollow cylinder can be solved with Semi-analytical Finite Element Method (SAFE) [12, 13]. Figure 2 shows the phase velocity dispersion curves for guided waves in a pipe with geometry and material parameters given in Table 1. Note that curves in different color denote modes with different circumferential orders.

In order to understand the behavior of guided waves, it is indispensable to study the wave structures. There are an infinite number of propagating modes for the hollow cylinder, the velocity field of the mth mode of Nth circumferential order can be written as follows:
\[ \psi_m^N(r, \theta) \exp \left( i \left( \omega t - k_m^N z \right) \right) = \left\{ \begin{array}{ll}
R_m^N (r) \Theta_m^N (N\theta) \mathbf{e}_r + \\
R_m^N (r) \Theta_m^N (N\theta) \mathbf{e}_\theta + \\
R_m^N (r) \Theta_m^N (N\theta) \mathbf{e}_z \exp \left( i \left( \omega t - k_m^N z \right) \right) \end{array} \right. \]  \tag{1}

where \( \omega \) and \( k \) are the angular frequency and wavenumber. Functions \( R(r) \) and \( \Theta(N\theta) \) denote the radial and angular distribution of the component of the velocity field produced by the normal mode with circumferential order \( N \) in \( m \)th family, respectively. The radial functions \( R(r) \) contain combination of Bessel (and modified Bessel) functions of the first and second order, while angular functions \( \Theta(N\theta) \) are sinusoidal functions \( \cos(N\theta) \) and/or \( \sin(N\theta) \).

**FIGURE 2.** Phase velocity dispersion curves for \( L(N,m) \) and \( T(N,m) \) modes in a steel pipe.

**TABLE 1.** The dimension and material properties of a steel pipe

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Material properties</th>
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<tbody>
<tr>
<td>Outer diameter</td>
<td>Thickness</td>
</tr>
<tr>
<td>OD(mm)</td>
<td>h(mm)</td>
</tr>
<tr>
<td>219</td>
<td>5</td>
</tr>
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</table>

Circumferential wave structure is expressed explicitly as a sinusoidal function, for example, \( \Theta(N\theta) = \cos(N\theta) \). It is observed that wavefronts of axisymmetric modes \( \Theta(N\theta) = \cos(0) = 1 \) are perpendicular to the pipe axis. But wavefronts of non-axisymmetric modes \( \Theta(N\theta) = \cos(N\theta) \neq \text{cons.} \) are not necessarily perpendicular to the pipe axis. Shown in Fig. 3 are unwrapped view of sample wavefronts for modes with circumferential order \( N \) equal 0 to 5. It is observed that the wavefront of a flexural mode make an angle with pipe circumference, which indicates that flexural waves propagate at an angle relative to the axial direction of a pipe.

A preliminary wavefront analysis indicates that a flexural guided wave is similar to a axisymmetric wave, except that it propagates at a helix angle relative to the axial direction of a pipe. Figure 4 shows the unwrapped view of flexural wave propagation in a pipe. Since the two solutions at either side of the unrolled plate must match, it is observed that there are an integer number of wavelengths \( N \lambda_z \) between two matching wavefronts.

Using simple trigonometry we get
\[ \tan \alpha = \frac{N \lambda_z}{2\pi R_u}, \]  \tag{2}
where \( N \) and \( \lambda \) are the circumferential order and the axial wavelength of the propagating mode, \( R_a \) is the pipe average radius.

**FIGURE 3.** Unwrapped view of some sample wavefronts for modes with circumferential order \( N \) equal 0 to 5.

**FIGURE 4.** Unwrapped view of flexural wave propagation in a pipe.

**Flexural Mode Excitation**

According to the new understanding of flexural modes in pipes, a method of pure flexural mode excitation is proposed. It has been shown that the excitation of a magnetostrictive transducer bonded around the circumference of a pipe or the simultaneous excitation of a ring of piezoelectric transducers around a pipe can excite axisymmetric modes effectively. As mentioned above, a wavefront analysis indicates that flexural modes are similar to axisymmetric modes, except that they propagate at a helix angle relative to the axial direction. Therefore, a magnetostrictive Helical Array Transducer (MHAT) is proposed to excite a specific flexural mode. The helix angle \( \alpha \) is determined by Eq. (2) as follows:

\[
\alpha = \tan^{-1} \left( \frac{N \lambda_p}{2\pi R_a} \right) = \tan^{-1} \left( \frac{N \omega_p}{2\pi f R_a} \right),
\]

where \( \omega_p \) is the phase velocity of the excited flexural mode, \( f \) is the excitation frequency. Helix angle of each flexural mode depends on its frequency, and can be viewed as function of frequency, this phenomenon is called helix angle dispersion. Shown in Fig. 5 are helix angle dispersion curves for flexural torsional modes with circumferential order \( N \) equal 1 to 8 in a steel pipe with geometry and material parameters given in Table 1. Note that the curves in different
color denote modes with different circumferential orders. The helix angle dispersion curves are essential for designing a MHAT to actuate a specific flexural mode.

**FIGURE 5.** Helix angle dispersion curves for flexural torsional modes in a steel pipe with parameters given in Table 1. Note that curves in different colors denote modes with different circumferential orders.

**MAGNETOSTRICTIVE HELICAL ARRAY TRANSDUCERS**

In this section, a detailed description of the proposed MHAT is given. Some basic features of a MHAT are summarized here. A MHAT is able to excite and receive a single dominant flexural torsional wave in a pipe. The transducer is wideband and can operate in a wide frequency range. The proposed transducer possesses the direction control ability, which enables a flexural wave generated in a single direction as the wave propagating in the opposite direction is canceled.

The configuration of a traditional MPT for exciting and receiving axisymmetric torsional waves is shown in Fig. 6(a). A pre-magnetized magnetostrictive patch is bonded onto or coupled with the outer surface of a pipe, a toroidal coil for supplying dynamic magnetic field is wrapped around the magnetostrictive patch. However, in a MHAT configuration, as shown in Fig. 6(b) thin magnetostrictive patch is helically bonded onto or coupled with the outer surface of a pipe. The helix angle of the transducer can be designed by using Eq. (3). The length of the patch L is then obtained as follows:

\[
L = \frac{2\pi R_o}{\cos(\alpha)},
\]

where \(R_o\) is the outer radius of the pipe, \(\alpha\) is the helix angle for exciting a specific flexural mode. The static bias magnetic field can be induced by pre-magnetization, permanent magnets, or a toroidal coil wound over the patch.

**FIGURE 6.** Panel (a) shows the configuration of the traditional MPT for exciting and receiving axisymmetric torsional waves. Panel (b) shows the configuration of the proposed MHAT for exciting and receiving predominant flexural torsional waves.
Figure 7(a) shows the side view of the proposed MHAT. A magnetostrictive patch (Hiperco 50A) is helically coupled with the outer surface of the pipe, the static bias magnetic field along the helical direction is induced by pre-magnetization. A novel compound comb coil that produce high-intensity dynamic magnetic field and generate SH waves with high power is wrapped around the helical magnetostrictive patch. The magnetic field directions generated by the excitation coil are indicated by arrows in Fig. 7(a). The dynamic magnetic field generated by the excitation coils is orthogonal to the static bias magnetic field, when the two magnetic fields are applied to the helical magnetostrictive patch bonded to the pipe, small rectangular elements in the patch will experience shear deformations as shown in Fig. 7(b). The compound comb coil contains two independent comb coils, the distance between the two coils is L, the spacing of each comb coil is D=2L, as shown in Fig. 7(a). A time delay Td is applied to the excitation coil, which enables a wave to be generated in a single direction, while the wave propagating in the opposite direction is canceled due to the offset. The proposed wideband MHAT can operate in a wide range of frequencies, and the time delay Td for each center frequency f can be calculated:

\[
Td = \frac{2n+1}{2} \frac{L}{f} C_g, \quad n = 0,1,2L
\]  

where \(C_g\) is the group velocity of the excited waves.

![Diagram of MHAT](a)

![Shear deformation](b)

**FIGURE 7.** Panel (a) shows the side view of the proposed MHAT. Panel (b) shows the SH wave driving mechanism by MHAT.

**VERIFICATION AND APPLICATION**

**Flexural Mode Excitation Experiment**

A Flexural mode excitation experiment is conducted to verify the proposed method. Excitation of flexural torsional mode T(3,1) at frequency \(f=64\text{kHz}\) in a steel pipe with parameters given in Table 1 is considered in this study.

The experiment setup is shown in Fig. 8. Magnetostrictive guided wave detecting instrument MSGW20U is employed and operates in the pitch-catch mode. A MHAT with 13-degree helix angle is wrapped around the outer surface of the pipe to excite a flexural torsional mode. Another miniature magnetostrictive transducer is placed at about 1.1m away from the transmitting transducer and moves around the circumference of the pipe to receive the wave...
field. Figure 9(a) shows the unwrapped view of the excited wave field. Sixty-nine signals are collected and the signals form a two dimensional time-circumference data matrix. A Fourier transform is conducted to analyze the circumferential orders of the excited waves. Figure 9(b) shows the normalized angular profile for the circumferential displacements of the excited wave. It is observed that the excited wave has three pairs of peaks and valleys distributed in the circumferential direction. Figure 9(c) shows the image of the circumferential orders for mode excitation at frequency $f=64\text{kHz}$, which indicates that the guided wave mode with circumferential order $N=3$ is excited. Flexural torsional mode $T(3,1)$ is effectively actuated in the experiment as expected, the proposed method is verified by an experiment.

![Diagram](image)

**FIGURE 8.** Experiment setup for exciting flexural mode. A helical magnetostrictive transducer acts as a transmitter, a miniature transducer that moves around the pipe acts as a receiver.

![Graphs](image)

**(a)** Snapshot of the propagating waves, **(b)** angular profile for the circumferential displacements of the propagating waves, **(c)** circumferential orders of the propagating waves, generated by a magnetostrictive helical transducer.

**Inspecting Spiral Welded Pipe Using Flexural Waves**

The proposed MHAT is used to inspect a spiral welded pipe with geometry dimensions and material properties given in Table 2. The forming angle of the spiral welded pipe is 70 degree, however, a flexural mode with helix angle $HA=70^\circ$ is badly dispersive and difficult to actuate. Therefore, flexural modes with helix angle $HA=20^\circ$ are selected to detect defects in the pipe, such that the excited flexural wave vector will be perpendicular to the spiral weld. An artificial notch with cross section loss (CSL) $CSL=2.7\%$ is introduced in the pipe. A MHAT with helix angle $HA=20^\circ$ as well as a traditional MPT are installed on the outer surface of the spiral welded pipe to detect the artificial defect, as shown in Fig. 10. Magnetostrictive guided wave detecting instrument MSGW20U is employed and operates in the pulse-echo mode. Both axisymmetric waves and flexural modes are adopted to detect the artificial notch.
TABLE 2. The dimension and material properties of a spiral welded pipe

<table>
<thead>
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<tr>
<td>Density</td>
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<td>ρ(Kg/m³)</td>
<td>E(GPa)</td>
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</table>

FIGURE 10. Setup of a spiral welded pipe inspection experiment using a 20-degree MHAT. An artificial notch with CSL=2.7% is introduced in the pipe.

The measured signals of axisymmetric waves and flexural waves are shown in Fig. 11. The artificial notch with CSL=2.7% could not be detected by the axisymmetric waves, which demonstrates the poor detection sensitivity of axisymmetric waves for inspecting spiral welded pipes. On the other hand, however, the reflected signal of the artificial notch is clearly shown in the measured signal of flexural waves, along with the multiple reflection signals of the spiral welds. The second signal in Fig. 11 was detected by a 20-degree MHAT installed two spiral welds away from the defect. The amplitude of the reflected signal decreases with the propagation distance. The SNR of the defect signal in the third signal is about 18dB, the artificial defect is effectively detected. The detection capability of the proposed MHAT for inspecting spiral welded pipe using flexural waves is verified by the experiment. However, the detection range is limited due to the energy loss caused by the numerous spiral welds.

FIGURE 11. Measured signals of inspecting a spiral welded pipe using axisymmetric wave and flexural wave, respectively.
CONCLUSION

In this paper, we proposed a magnetostrictive Helical Array Transducer (MHAT) for selectively exciting and receiving a single predominant flexural torsional wave in a pipe and inspecting spiral welded pipes using flexural waves. A wavefront analysis indicates that a flexural wave propagates at a helix angle with respect to the pipe axis, and the helix angle dispersion curves for flexural modes are calculated. A MHAT is proposed according to the new understanding of flexural waves. In a MHAT configuration, a pre-magnetized magnetostrictive patch is helically bonded onto or coupled with the outer surface of a pipe, a novel compound comb coil that produce high-intensity dynamic magnetic field is wrapped around the helical magnetostrictive patch and acts as a excitation coil. The wideband MHAT possesses the direction control ability. A verification experiment indicates that flexural torsional mode $T(3,1)$ at center frequency $f=64\text{kHz}$ is effectively actuated by a MHAT with 13-degree helix angle. Flexural torsional modes $T(N,1)$ with circumferential order $N$ equals 1 to 5 are selected to inspect a seamless steel pipe, artificial defects are effectively detected by the proposed MHAT. A 20-degree MHAT is used to inspect a spiral welded pipe. An artificial notch with CSL=2.7%, that could not been detected by axisymmetric wave, is effectively detected by the MHAT, the detection capability for inspecting spiral welded pipes is verified. Pipeline inspection using flexural guided waves with can be supplemental to current axisymmetric inspection in order to improve the probability of an accurate inspection process.

ACKNOWLEDGMENTS

The authors acknowledge the supports from the National Natural Science Foundation of China under Grant nos. 61271084 and 51275454 and the Fundamental Research Funds for the Central Universities.

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