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Helical comb magnetostrictive patch transducers for inspecting spiral welded pipes using flexural guided waves

Xiaowei Zhang [a], Zhifeng Tang [b,*], Fuzai Lv [a], Xiaohong Pan [a]

[a] Institute of Modern Manufacturing Engineering, Zhejiang University, China
[b] Institute of Advanced Digital Technologies and Instrumentation, Zhejiang University, China

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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 helical comb magnetostrictive patch transducer (HCMPT) is proposed for selectively exciting a single predominant flexural torsional guided wave in a pipe and inspecting spiral welded pipes using flexural waves. A HCMPT contains a pre-magnetized magnetostrictive patch that is helically coupled with the outer surface of a pipe, and a novel compound comb coil that is wrapped around the helical magnetostrictive patch. The proposed wideband HCMPT possesses the direction control ability. A verification experiment indicates that flexural torsional mode $T(3,1)$ at center frequency $f = 64$ kHz is effectively actuated by a HCMPT with 13-degree helix angle. Flexural torsional modes $T(N,1)$ with circumferential order N equals 1–5 are selected to inspect a seamless steel pipe, artificial defects are effectively detected by the proposed HCMPT. A 20-degree HCMPT 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.

1. 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 an angled notch or a spiral weld, as shown in Fig. 1. Therefore, axisymmetric waves have poor detection sensitivity for oblique defects in seamless steel pipes and defects in spiral welded pipes. The application of flexural modes tends to provide enhanced ability to detect defects, especially detection of oblique defects in seamless steel pipes and defects in spiral welded pipes, compared to the use of axisymmetric modes. A flexural wave that propagates at an angle with respect to the pipe axis can provide for constructive interference with angled defects such that the reflection coefficient is bigger than that of axisymmetric waves. 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). Therefore, pipeline inspection using flexural guided waves can be supplemental to current axisymmetric inspection in order to improve the probability of an accurate inspection process.

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

* Corresponding author.
E-mail address: tangzhifeng@zju.edu.cn (Z. Tang).

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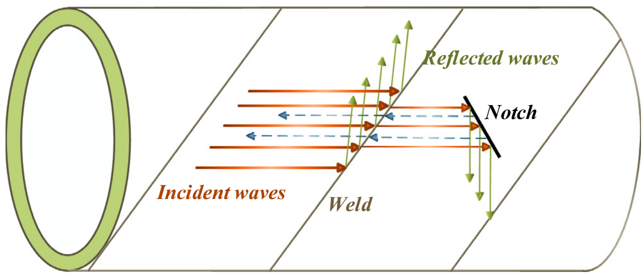

Fig. 1. An axisymmetric wave experiences destructive interference when it encounters an angled notch or a spiral weld.

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.

The real-time phased array focusing technique is utilized for focusing a significant portion of wave energy at a desired point of the pipe. Li et al. [12], Hayashi et al. [13], Luo et al. [14], Zhang et al. [15] and Mu et al. [16] used superposition of angular profiles of flexural modes to focus wave energy at a desired point. Synthetic focusing technique is also utilized for defect imaging in pipes. Hayashi et al. [17] used a time-reversal technique to reconstruct an image of the defects. Davies et al. [18] found that the common source method (CSM) is the most satisfactory of commonly used synthetic focusing algorithms for defects imaging in pipes. Velichko et al. [19] described a method for processing data from transducer array on a pipe. It was shown that for certain configuration of an array, the total focusing method (TFM) can be applied, which allowed the array to be focused at every point on a pipe in both transmission and reception. Both real-time and synthetic focusing methods of guided waves in pipes involve analyzing and implementing flexural modes. Therefore, formation of a framework of flexural guided wave mechanics in pipes is of great significance for optimizing real-time and synthetic focusing methods of guided waves in pipes.

The three main types of transducers that are currently in service for guided wave inspection of pipelines are piezoelectric transducers, magnetostrictive transducers and periodic-permanent-magnet electromagnetic acoustic transducers. Magnetostrictive transducers are more cost-effective, involve relatively simpler fabrication process and have higher possible transduction efficiency than other transducer types. Different kinds of magnetostrictive transducers have been developed in recent years. Kwun et al. [20] introduced several magnetostrictive transducer configurations and discussed various scientific and engineering applications. Kim et al. [21] proposed a new transducer configuration using several pieces of nickel strips installed at 45° with respect to the pipe axis, to avoid pre-magnetization and to improve the transduction efficiency. Cho et al. [22] proposed a noncontact method to generate and receive torsional waves in rotating shafts by set of magnetostrictive patches and a solenoid. Kim et al. [23] developed a novel Terfenol-D transducer for guided wave inspection of a rotating shaft. Kim et al. [24] employed the topology optimization method to find an optimal magnetic yoke configuration maximizing the magnetic flux density and improving flux uniformity in the strips, which increased the transducer signal output. Lee et al. [25] presented some experiment results obtained with a circular magnetostrictive patch transducer with a planar solenoid array coil, the radiation patterns obtained from the experiments are analyzed by a theory based on a two-dimensional distributed line source model. Kim et al. [26] proposed a crossed-coil magnetostrictive sensor consisting of a solenoid coil, a toroidal coil, and a ferromagnetic patch for generating and detecting torsional waves for pipe inspection. Kim et al. [27] developed a circumferential phased magnetostrictive patch transducer array that can focus shear-horizontal waves at any target point on a cylindrical surface of a pipe. Liu et al. [28] also proposed a torsional mode magnetostrictive patch transducer array employing a modified planar solenoid array coil for pipe inspection. Seung et al. [29] developed an omni-directional shear-horizontal wave magnetostrictive patch transducer for plates. A comprehensive review of magnetostrictive patch transducers and applications in ultrasonic nondestructive testing of waveguides was given by Kim et al. [30]. Researchers have done excellent work on the subject of magnetostrictive guided wave transducers, however, magnetostrictive transducers that are able to excite and receive a single dominant flexural wave in a pipe haven been rarely reported in the literature.

In this paper, a novel magnetostrictive transducer is proposed for exciting and receiving predominant flexural waves. The dispersion curves for both axisymmetric and flexural modes are calculated by using Semi-analytical Finite Element Method. Both radial and circumferential wave structures are studied in order to understand the behavior of guided waves in a pipe. 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 helical comb magnetostrictive patch transducer (HCMPT) is then developed to excite and receive a single predominant flexural torsional wave in a pipe. The wideband HCMPT possesses the direction control ability. A detailed description of the proposed HCMPT is given. A verification experiment indicates that flexural torsional mode $T(3,1)$ at center frequency $f = 64$ kHz is effectively actuated by a HCMPT with 13-degree helix angle. Flexural torsional modes $T(N,1)$ with circumferential order N equals 1–5 are selected to inspect a pipe, the defect detection ability of the proposed transducer is verified by experiments. A 20-degree HCMPT 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.

2. Theory

2.1. Analysis of flexural guided waves

The guided wave behavior in a spiral welded pipe is approximately the same as that in a seamless steel pipe with the same