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Guided torsional wave generation of a linear in-plane shear piezoelectric array in metallic pipes

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ABSTRACT

Cylindrical guided waves based techniques are effective and promising tools for damage detection in long pipes. The essential operations are generation and reception of guided waves in the structures utilizing transducers. A novel in-plane shear (d_{36} type) PMNT wafer is proposed to generate and receive the guided wave, especially the torsional waves, in metallic pipes. In contrast to the traditional wafer, this wafer will directly introduce in-plane shear deformation when electrical field is conveniently applied through its thickness direction. A single square d_{36} PMNT wafer is bonded on the surface of the pipe positioned collinearly with its axis, when actuated can predominantly generate torsional (T) waves along the axial direction, circumferential shear horizontal (C-SH) waves along circumferential direction, and other complex cylindrical Lamb-like wave modes along other helical directions simultaneously. While a linear array of finite square size d_{36} PMNT wafers was equally spaced circumferentially, when actuated simultaneously can nearly uniform axisymmetric torsional waves generate in pipes and non-symmetric wave modes can be suppressed greatly if the number of the d_{36} PMNT wafer is sufficiently large. This paper first presents the working mechanism of the linear d_{36} PMNT array from finite element analysis (FEA) by examining the constructive and destructive displacement wavefield phenomena in metallic pipes. Furthermore, since the amplitude of the received fundamental torsional wave signal strongly depends on frequency, a series of experiments are conducted to determine the frequency tuning curve for the torsional wave mode. All results indicate the linear d_{36} PMNT array has potential for efficiently generating uniform torsional wavefield of the fundamental torsional wave mode, which is more effective in monitoring structural health in metallic pipes.

1. Introduction

Modern industries rely heavily upon the pipeline infrastructure for the supply and distribution of required materials, which normally are high-temperature, high-pressure, explosive, inflammable gas/liquid, toxic, even radiant fluid. The pipelines usually achieve a very long operating life of 40–50 years. During their operation, pipelines can suffer from a wide variety of damage and aging defects. Some of the most common causes of failure in pipelines are corrosion, stress cracking, seam weld cracks, material flaws, and externally induced damage by excavation equipment [1]. In the USA, over 50% of the 10^6 km oil and gas pipeline system is over 40 years old [2]. Increasing in the probability of pipeline accidents is a universal concern to all countries.

Cylindrical guided waves based techniques have been proven to be effective and promising tools for the damage detection in pipes, in which guided wave can propagate along the span (axial direction) of the pipe at long distances as well as resonate the circumferential direction. For the former, they are further divided into longitudinal modes (L), flexural modes (F) and torsional modes (T); and for the latter, two kinds of circumferential guided wave modes exist: circumferential "plane-strain" (C-PS) waves with non-zero displacement components, u_r and u_θ [3], analogous to the Rayleigh waves in semi-infinite solids and Lamb waves in plates, and circumferential shear-horizontal (C-SH) waves with only non-zero displacement component, u_z, have also been

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discussed [4]. Note that torsional waves are circumferentially polarized waves propagating along the axial direction; while the C-SH waves are axially polarized waves propagating along the circumferential direction. In addition, cylindrical Lamb-like waves exist along any helical direction and are different from Lamb waves in plates and axial waves in pipes. Among above guided wave modes in pipes, the fundamental torsional wave mode T(0, 1) is preferred to analyze due to its simple wave physics and non-dispersive characteristics.

Modes of cylindrical guided wave excited or detected depend greatly on how the transducers interact with the structures and/or damages to be monitored. As early as 1979, piezoelectric ultrasonic transducers have been used by Silk and Bainton [5] to investigate ultrasonic wave modes experimentally in both straight and U-form thin-walled ferritic steel tubes. Alleyne and Cawley [6] presented a linear (d_{31}) piezoelectric transducer array which comprises sixteen piezoelectric elements evenly distributed along the circumferential direction at one end of the pipe to both excite and receive L and F wave modes. Due to the transverse in-plane isotropy of the piezoelectric materials; that is $d_{31} = d_{32}$, the in-plane deformation introduced by the conventional piezoelectric transducers is incapable of exciting torsional waves; only L and F wave modes propagating along the axial direction were thus studied.

For a thickness-shear (d_{15} or d_{24}) piezoelectric material, its poling direction is perpendicular to a driving electric field direction. Therefore the d_{15} piezoelectric material is easily depoled during its operation, especially in piezoelectric single crystals. However, in the in-plane shear (d_{36}) piezoelectric material, its poling direction is parallel to a driving electric field direction. Thus the d_{36} piezoelectric material is more stable during its operation than d_{15} piezoelectric material. Further the d_{36} in-plane shear component can be repolarized since the poling direction is the same as the working electrode direction.

If the thickness-shear (d_{15} or d_{24}) deformation mode of the piezoelectric wafer is employed to generate torsional waves, often they would need to be constrained in some manner such that non-dispersive fundamental torsional waves can be generated [7]. Liu et al. [8] used sixteen shear piezoelectric wafers around the circumference to measure the reflection coefficient of torsional waves in a steel pipe with longitudinal and circumferential defects. Ratassepp et al. [9] studied the interaction of the T(0, 1) torsional mode with an axial defect in a steel pipe. Torsional waves were generated and received from a ring that made up of two rows of shear piezoelectric transducer elements, each with sixteen piezoelectric wafers. Magnetostrictive transducers can be also used to excite and detect the torsional wave mode wave. Kwun et al. [10,11] developed a guided-wave magnetostrictive sensor (MsS) that can be mounted on pipes for long-term structural health monitoring. It was operated in the torsional wave mode for piping. This type of transducer requires bias magnetic field with coils for converting electrical into magnetic energy for wave generation and reception. For detecting the damage in nonferrous materials, an MsS can be placed on a thin nickel strip that was bonded onto the structure. The signal generated from the MsS can be coupled to the nonferrous structure through the thin strip, thus exciting guided waves [12]. Kannan et al. [13] reported an improved magnetostrictive technique that uses polymeric magnetic tape material, which increases efficiency, reduces cost and enhances long-term survivability. A linear phased array around the pipe is another significant attempt to obtain clearer damage information in pipes. Li and Rose [14] used a circumferential phased array to implement a circumferential scan with focused, guided wave beams (L mode), which leads to the detection of smaller defects as a result of stronger focused beams, while Kim et al. [15] used a linear phase array of magnetostrictive transducers along the circumferential direction to excite shear-horizontal waves. The array using six transducers can generate and receive shear horizontal (SH) waves individually with controlled time delays and amplitudes. Combined with time-reversal technique, its effectiveness was demonstrated in several multiple cracks detection experiments.

It is worth noting that piezoelectric macro-fiber composite (MFC) can also be employed to generate torsional waves and detect the axial cracks, because the MFC exhibits in-plane anisotropy due to the piezoelectric fibers aligned in a given direction. In comparison with conversional piezoelectric ceramic, MFC offers high performance, flexibility and reliability. Cui et al. [16] bonded four MFCs (P1 type, d_{33} mode) on the surface of the aluminum pipe at 45° oriented from the longitudinal axis, therefore all L, F and T waves are generated and received. By exciting a five-cycle Hanning windowed toneburst signal with center frequency 160 kHz, all wave packets were well separated and reflected to different cracks sizes.

As stated above, magnetostrictive transducers, thickness-shear piezoelectric transducers and MFC (d_{33} mode) can generate torsional wave modes, but the first two transducers usually operate with additional constraining mechanisms, resulting in a larger dimension in comparison with piezoelectric wafers. At present, MFC seems the only option with small sizes. Recently, a new PMNT wafer was proposed to generate and detect the SH waves on plates [17,18]. Note that deformation introduced by the SH waves in plates are equivalent to torsional waves in pipes. This unique characteristic is due to the large piezoelectric coefficient d_{36} in its piezoelectric constant matrix. The direct piezoelectric effect of piezoelectric coefficient d_{36} indicates that under external in-plane shear stress τ_{12}, the charge is induced on a face perpendicular to the poled z-direction. The corresponding converse piezoelectric effect is when the external electric field is applied in the z-direction, the response is the in-plane shear deformation experienced by the material on the surface. In piping structures, this will result in both axial torsional waves and circumferential shear horizontal (C-SH) waves and other complex waves propagating in helical directions. This paper investigates the application of the proposed linear in-plane shear PMNT array on the metallic pipe by simulation and experiments.

2. Cylindrical guided waves in pipe

Cylindrical guided waves in pipe are more complex than those in plate-like structures, in which there exist only symmetric (S) mode, anti-symmetric (A) mode and SH mode waves. Guided waves in hollow pipes propagating in the axial direction and resonating in the circumferential direction were first studied by Gazis [19], who reported the exact solutions of the Pochhammer–Chree (PC) frequency equation, describing the frequency wavenumber relation. For the wave propagating along the axial direction, these solutions lead to three different classes of wave propagating modes: the axisymmetric torsional modes T(0, n) and longitudinal modes L(0, n), and the non-axisymmetric flexural modes F(m, n). Here, m stands for the circumferential order and n stands for the wave family number. They are all dispersive except the fundamental torsional mode, T(0, 1). In addition, Zhao and Rose [4] investigated the guided shear horizontal wave propagating in the circumferential direction of a hollow cylinder, referred to C-SH in this paper. Except C-SH$_0$ mode which is slightly dispersive for thin

Table 1
Non-zero displacement components for the five cylindrical guided wave modes in pipes.

Modes	T(0, n)	L(0, n)	F(m, n)	C-SH$_n$	C-PS$_n$
Displacement components	u_θ	u_r, u_z	u_r, u_θ, u_z	u_z	u_r, u_θ