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Excitation of dominant flexural guided waves in elastic hollow cylinders using time delay circular array transducers

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

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

HIGHLIGHTS

- The NME is adopted to analyze the excitation of dominant flexural waves in pipes.
- A time delay circular array transducer is proposed to excite dominant flexural mode.
- Expression to calculate time delay for exciting a specific flexural mode is given.
- Numerical evaluations indicate that dominant flexural waves are efficiently excited.

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ABSTRACT

A time delay circular array transducer (TDCAT) is proposed to selectively excite a dominant flexural guided wave mode in an elastic hollow cylinder. The classical Normal Mode Expansion method (NME) is adopted to disseminate the forced response and perturbation analysis of a hollow cylinder with respect to a time delay circular array loading. A single dominant flexural mode is effectively excited in a hollow cylinder by a TDCAT with appropriate time delay parameters. The expression for calculation of time delay parameters to excite a specific flexural mode is given. Numerical evaluations that demonstrate the generation of dominant flexural modes in elastic hollow cylinders are carried out for both torsional and longitudinal flexural modes. A TDCAT with eight elements is recommended for practical flexural guided wave utilizations after studying the influence of element number on flexural wave excitation.

1. Introduction

Ultrasonic guided waves have already been demonstrated by various research work to have great application potential in on-line Non-Destructive Evaluation (NDE) and long-term Structural Health Monitoring (SHM) of pipelines in various industries [1], due to various corresponding advantages such as single-point excitation, long detection range, high inspection efficiency, and 100% cross-section coverage. Axisymmetric guided wave modes, such as $T(0, 1)$ and $L(0, 2)$, have been applied to detect and locate defects that cause changes in the cross section of a pipe. The detection sensitivity for detecting transverse defects is relatively high, while the detection sensitivity for detecting longitudinal defects and oblique defects is somewhat low. Besides, methods for classifying defects are limited when axisymmetric modes are applied for inspecting pipes. Pipeline inspection using flexural guided waves can be supplemental to current axisymmetric inspection in order to improve the

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

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probability of an accurate inspection process. In addition, inspection using flexural guided waves is likely to be a potential solution for complex situations such as inspection of spiral-welded pipes and detection of defects beyond elbows.

Flexural guided waves in pipes have been known for decades, excitation of flexural guided waves has also been considered in the literature. Gazis [2] had shown that there exist 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. [3] with Normal Mode Expansion Method (NME), to obtain the amplitude factors of different guided wave modes. Li et al. [4] studied the excitation and propagation of non-axisymmetric longitudinal waves by using NME, with different sources such as angle beam, normal beam and comb transducers considered. The angular profile was calculated by taking into account the amplitude factors of every excited mode. Sun et al. [5] studied flexural torsional wave mechanics and focusing by using NME. The Four-Dimensional Tuning Process was implemented to control angular profiles for energy focusing. Liu et al. [6] presented a plate ray perspective for elastic wave propagation in hollow circular cylinders. A helical inter-digital transducer was designed for the excitation of flexural modes. However, most of the current methods for exciting flexural modes suffer from two disadvantages. First, a single dominant flexural mode cannot be excited and multiple modes will bring difficulties in interpretation of the received signal. Second, the excited flexural waves cannot cover the entire surface of a pipe. Therefore, excitation of dominant flexural modes that 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. [7], Hayashi et al. [8], Luo et al. [9], Zhang et al. [10] and Mu et al. [11] 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. [12] used a time-reversal technique to reconstruct an image of the defects. Davies et al. [13] found that the common source method is the most satisfactory of commonly used synthetic focusing algorithms for defects imaging in pipes. Velichko et al. [14] described a method for processing data from a transducer array on a pipe. It was shown that for certain configuration of an array, the total focusing method 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 application of flexural modes. Therefore, analyzing and implementing flexural modes is of great significance for optimizing real-time and synthetic focusing methods of guided waves in pipes.

In this article, the classical NME is adopted to analyze the excitation of dominant flexural guided waves in elastic hollow cylinders. The potential of partial loading and circular array loading for exciting dominant flexural modes is incorporated. A time delay circular array transducer (TDCAT) is proposed and analyzed, the time delay is deliberately designed and a single dominant flexural mode is effectively excited. Summarized finite element numerical evaluations demonstrate the generation of dominant flexural guided wave modes in elastic hollow cylinders, and the theoretical prediction is verified by numerical simulations.

2. Guided waves in hollow cylinders

2.1. Theory

Guided waves in hollow cylinders may travel in either 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 θ 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 ($N \neq 0$, also known as flexural modes).

The wave behavior in a hollow cylinder can be described by solving the governing equations with appropriate boundary conditions. For an elastic isotropic traction-free hollow cylinder (Fig. 1), the Navier's governing wave equation can be written as [1]:

$$\mu\nabla^2\mathbf{u} + (\lambda + \mu)\nabla\nabla\cdot\mathbf{u} = \rho\frac{\partial^2\mathbf{u}}{\partial t^2}$$

$$\sigma_{rr} = \sigma_{r\theta} = \sigma_{rz} = 0 \quad \text{on } r = R_i \text{ and } r = R_o,$$

where $\mathbf{u}$ represents the displacement field, which is a function of the three cylindrical coordinates and time; ρ denotes the density; μ and λ represent the Lamé constants.

Helmholtz decomposition can be utilized to simplify the problem:

$$\mathbf{u} = \nabla\Phi + \nabla\times\mathbf{H}, \tag{2}$$

where Φ is the dilatational scalar potential and $\mathbf{H}$ denotes the equivoluminal potential. In addition to the traction-free boundary condition, the gauge invariance condition in an infinite long hollow cylinder is applicable here:

$$\nabla\cdot\mathbf{H} = 0. \tag{3}$$