Ultrasonics 57 (2015) 190–197

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

The reflection of guided waves from simple dents in pipes

Shuyi Ma [a], Zhanjun Wu [a,b,*], Yishou Wang [a], Kehai Liu [a]

[a] State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China
[b] The Department of Civil and Environmental Engineering, the University of Illinois at Urbana-Champaign, 205 North Mathews Ave., Urbana, IL 61810-2352, USA

ARTICLE INFO

Article history:
Received 25 March 2014
Received in revised form 9 November 2014
Accepted 21 November 2014
Available online 28 November 2014

Keywords:
Pipe inspection
Ultrasonic guided waves
Dent
Deformation rate

ABSTRACT

Guided elastic waves have been anticipated as a rapid screening technique for pipe inspection. Dents occurring in pipes are a severe problem which may lead to the possibility of pipe failure. A study of the reflection characteristics of guided waves from dents of varying geometrical profile in pipes is investigated through experiments. Dented region is represented by a series of circumferential cross-sections and its geometric parameters are described by axial length and the maximum and minimum outer diameters. Both single and double sided dents are mechanically simulated in hollow aluminum pipes and then experimentally tested by exciting the longitudinal L(0,2) mode. A quantitative parameter, so-called deformation rate relating to the maximum and minimum outer diameters of the dents is defined to evaluate the effect of the extent of the deformation on the reflection. For both types of dents, it is shown that the reflection coefficients of the L(0,2) mode are all approximately a linear function of their respective deformation rates. Mode conversion occurs at the dents and reflections of the F(1,3) mode are identified. The results show that the amplitude of the reflected F(1,3) mode is generally higher when the dent has stronger non-axisymmetric features.

1. Introduction

Dents or deformation defect in pipes is a severe problem which affects many industries. The extension of deformation caused by various complex loadings can lead to total collapse of the cross section of pipes. Therefore, it is crucial to detect the pipe wall deformation in order to guarantee the structural safety. Current methods for pipe deformation detection are mostly based on visual inspection. The standard approach is to have a color, high-resolution video camera and lighting system on a wheeled platform, which is capable of traveling across and the through the pipe while videotaping the inner surface of the pipe [1]. However, this method depends on very good visibility and may not be able to acquire high-quality images in harsh environments. Ultrasonic nondestructive testing techniques can also be used to detect deformation in pipes. The inspection system employing ultrasonic rotating scanners can create a three dimensional (3D) image of the internal pipe wall [2]. The limitation of this method is that it can only work in liquid filled pipes. In addition, these methods described above require the access to the inside of the pipe which is not feasible in many practical situations.

The cylindrically guided waves propagating along the pipe may be an attractive method for deformation detection, because of their capability of inspecting a long length of pipe from a single point [3,4]. Furthermore, access to the inside of the pipe is not required as the propagating modes may be excited on the outer wall of the pipes. The basic idea is that the presence of deformations in pipes will reflect the guided waves propagating along the pipes and change their propagation characteristics. The measurements of these reflected waves can lead to deformation detection. Na and Kundu [5] performed an experimental study on the detection of a dent in underwater pipe using flexural guided waves, focusing on the effect of the different incident angles of ultrasonic transducers and frequencies on the received signal amplitude. Ma et al. [6] carried out a feasibility study of the dent deformation detection in pipes using the L(0,2) guided wave mode with an emphasis on the effect of the dent depth on the amplitude of the reflected L(0,2) mode. However, the dent depth cannot accurately characterize the total pipe cross-section which could contain multiple dents.

The interaction of cylindrically guided waves with discontinuities in the geometry of the waveguide is a topic that has stimulated a great deal of interest. The reflected or transmitted signals are closely related to the geometric parameters of discontinuities in pipes. Therefore, it is believed that a discontinuity in a pipe can be identified and even characterized by analyzing the effects of its geometric parameters on the reflection or transmission

* Corresponding author at: State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China. Tel.: +86 411 84708646.

E-mail address: wuzhj@dlut.edu.cn (Z. Wu).

http://dx.doi.org/10.1016/j.ultras.2014.11.012
0041-624X/

signals. For example, Lowe et al. [7] reported that the mode conversion in reflection from an axisymmetric mode to flexural modes enables discrimination between axially symmetric reflectors such as circumferential welds and non-axially symmetric defects. Demma et al. [8] considered the amplitude of the reflected mode converted signal and concluded that it is possible to estimate the circumferential extent of a corrosion defect by evaluating the ratio between the flexural reflected component and the axisymmetric reflected component. However, due to the diversity and complexity of the discontinuities in pipes, the problem of identifying and characterizing the discontinuities has not been figured out yet. The research about the interaction of guided waves with different discontinuities is still ongoing.

In this study, an attempt is made at developing a relationship between the reflection of guided waves and the geometric characteristics of deformations in pipes. First of all in Section 3 the geometric characteristics of two typical types of dent models -single and double sided dents- are analyzed and their geometric parameters are defined. In Section 4, both types of dents with varying the geometrical profiles are mechanically simulated in hollow aluminum pipes and then experimental measurements are carried out, respectively. The experimental results are presented in Section 5, and the effect of the geometric characteristics and parameters of these dents on the reflected signals is analyzed.

2. Guided mode properties

The properties of guided wave modes in pipes are complicated, but they have also been well understood. Fig. 1 shows the group velocity dispersion curves over a frequency range of 0–500 kHz for an aluminum pipe (16 mm outer diameter and 1 mm wall thickness). It is seen from Fig. 1 that there are three types of guided wave modes propagating in the axial direction of the pipe. The modes are labeled L(0, n), T(0, n) and F(m, n), respectively, referring to axisymmetric longitudinal, axisymmetric torsional and non-axisymmetric flexural modes [9]. The first index m indicates the order of harmonic variation of displacement and stresses around the circumference and the second index n is a counter variable. It is clear from Fig. 1 that multiple modes can potentially propagate at a given frequency and the modes are also generally dispersive (the velocity of a particular mode changes with frequency) so that the original wave packet is distorted as it travels along the pipe. This phenomenon makes interpretation of the signals difficult and also leads to low signal-to-noise ratio problems. For practical purposes, it is generally desirable to excite a single guided wave mode in a non-dispersive frequency region, and much of the considerable effort has been concentrated on this by many researchers [3,7].

The longitudinal L(0,2) guided wave is one of the most attractive modes to be used in practical pipe inspection. Previous studies and experimental experience [7,8] have shown that this mode has the following advantages: (1) Almost non-dispersive over a wide frequency band, for example, the frequency range 200–300 kHz is a particularly attractive choice for the above-mentioned aluminum pipe, according to the dispersion curves shown in Fig. 1. (2) Fastest group velocity, it will be the first signal to arrive at the receiver and so can readily be separated by time domain gating. (3) Easier to be excited without producing flexural modes by applying uniform excitation over the circumference of the pipe. (4) Sensitive to both internal and external defects as its mode shape consists approximately uniform axial motion throughout the pipe wall, as shown in Fig. 2. Thus, the L(0,2) guided wave mode was selected in this study for pipe deformation assessment.

3. Characterization of the pipe deformation

The deformations that exist in pipes usually have complex, irregular cross-sectional geometries in practice. In order to investigate the reflection characteristics of guided wave modes from deformation defects, this study proceeds with the work by taking into account the simplified case of local dent deformations [10–12]. Fig. 3 presents the schematic of the models of two typical types of dents in pipes, named single and double sided dent, respectively. Each of the dents can be approximately represented as a longitudinal cross-section and a series of circumferential cross-sections, as shown in Fig. 3(a) or (b). D is the outer diameter of the un-dented pipe. In order to analyze the relationship between the reflection signals and the geometric parameters of the dent, it is necessary to identify the geometric characteristics of these dents. With regard to the models of both dents, we focus on three circumferential cross-sections: the initial section just before the dent occurs, the deepest section where the deformation is severe and the terminal cross-section just after the deformation in the direction of excitation waves, which are denoted as AA', BB' and CC', respectively. Here, we present the deepest circumferential cross-section profiles (BB', solid line) of both types of dents, as shown in Fig. 3 (a) or (b). O is the geometric center of the original pipe circumferential cross-section (dashed line). Taking O as the geometric center, a Cartesian coordinate system is built up, where x, y and z represent the simple Cartesian coordinates as shown in Fig. 3. Dent depth is defined as the maximum reduction in the

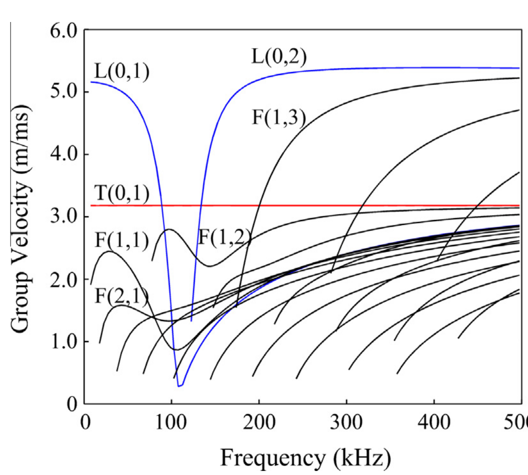

Fig. 1. Group velocity dispersion curves for an aluminum pipe (outer diameter 16 mm and wall thickness 1 mm).

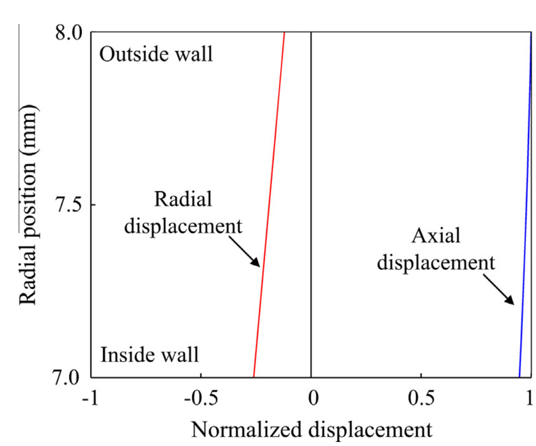

Fig. 2. L(0,2) mode shapes in an aluminum pipe (outer diameter 16 mm and wall thickness 1 mm) at 240 kHz.