Ultrasonics 54 (2014) 1078–1087

Contents lists available at ScienceDirect

Ultrasonics

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

High order shear horizontal modes for minimum remnant thickness

Pierre Belanger [*]

Département de Génie Mecanique, École de Technologie Supérieure, 1100, rue Notre-Dame Ouest, Montréal, Québec H3C 1K3, Canada

ARTICLE INFO

Article history:
Received 2 July 2013
Received in revised form 17 December 2013
Accepted 28 December 2013
Available online 17 January 2014

Keywords:
Guided waves
Shear horizontal waves
Cutoff frequency
Thickness gauging
Corrosion

ABSTRACT

Thickness mapping in aging structures suffering from corrosion is challenging especially when the structure is only partially accessible. In plates the high order shear horizontal guided wave modes all have a cutoff frequency thickness product below which they cannot propagate. This property is potentially attractive to estimate the minimum remnant thickness between two transducers. When using a source and a sensor array it is possible to control the number of modes being excited and the size of the region interrogated by the technique. Finite element simulations were used to show that by exciting multiple guided wave modes simultaneously and identifying which modes are received by a sensor array it is possible to estimate the minimum remaining thickness along the propagation path. Initial experimental results showed excellent agreement with the finite element simulations when the plate is uniform and with a thickness reduction between the source and the sensor arrays the minimum remnant thickness was underestimated by approximately 20%.

1. Introduction

Corrosion is a common problem across multiple industries, petrochemical, aerospace or civil infrastructure to name a few. The corrosion is in many cases partially accessible or completely inaccessible which prevents visual inspection or the use of more advanced methods such as ultrasonic thickness gauging [1] or eddy current techniques [2]. The latter two techniques are slow and tedious when a large area must be scanned. The need for a rapid, accurate, long range inspection technique to estimate the remnant thickness in a structure is therefore high.

Low frequency guided waves are frequently used to screen large area of pipes or other structures for cracks, corrosion and other types of defect [3–7]. However these techniques can only provide a rough estimate of the remnant thickness of the structure the waves are propagating through. Tomography algorithms can be used with low frequency guided waves to construct an accurate map of the remaining thickness [8–11]. The algorithms used in tomography are complex and require specific transducer array geometries.

A different approach using high order guided wave modes to size cracks and corrosion has been proposed in [12]. The reflection of the high order guided wave mode clusters was shown to be correlated to the depth of the defects both in simulations and experiments.

The aim of this paper is to examine the possibility of using the high order guided wave modes cutoff property to obtain the minimum thickness between a source and a sensor. Such a technique could be used to either get the minimum remaining thickness in the path between a source and sensor or scan multiple paths to produce a map of the minimum remaining thickness. The principle investigated in this paper is to excite a large number of guided wave modes and have a sensor on the other side of the area of inspection to detect the guided wave modes that propagate through the inspection area. If the guided wave modes detected by the sensor can be identified, it is possible to obtain an approximation of the minimum thickness between the source and the sensor. This idea, using a single guided wave mode, has been investigated in the past [13–17]. However the limitation of this technique when using a single mode is that it is only possible to evaluate whether the remnant thickness is smaller or larger than a given value depending whether the mode is detected or not. Moreover for this technique to interrogate only the path between two transducers the input signal frequency and transducer must be chosen carefully.

This paper investigates the possibility of using multiple guided wave modes to obtain an estimation of the thickness. The first section details the theoretical principle in order to use the cutoff property of the high order guided wave modes as well as the principle for the excitation and detection of the guided wave modes of interest with a transducer array. The second section discusses details of the finite element (FE) simulations for randomly varying thickness in the area of inspection. Finally in the third section the challenges of the initial experimental implementation are examined.

---

[*] Tel.: +1 514 396 8456.
E-mail address: pierre.belanger@etsmtl.ca

0041-624X/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.12.013

2. Theory

Fig. 1 presents (a) the Lamb wave and (b) the shear horizontal (SH) wave phase velocity dispersion curves as a function of the frequency thickness product in an aluminium plate (E = 70.8 GPa, $\nu = 0.34$ and ρ = 2700 kg/m^3) computed using the DISPERSE software package [18].

Only the three fundamental modes (A_0, S_0 and SH_0) can propagate at all frequency thickness products. The high order modes exhibit a cutoff frequency thickness product where the phase velocity approaches infinity. These cutoffs represent the frequency thickness product at which a standing transverse wave is present across the thickness of the waveguide [19]. Below the cutoff frequency thickness product of any given high order mode, no energy of this given mode can propagate in the structure [20]. Traditionally ultrasonic guided waves have been used below the cutoff frequency thickness product of the high order modes, the signal processing being much simpler because only the three fundamental modes can propagate.

For guided waves the presence of corrosion is fundamentally equivalent to a change in the thickness of the waveguide [13]. The significance of the high order modes cutoff property is that if a thickness reduction is present along the propagation path such that the frequency thickness product was shifted below the cutoff frequency thickness product of a given mode, no energy of that mode would propagate through the reduced thickness region. The energy of the mode would be converted into lower order modes and/or reflected. Nurmalia et al. [21] recently demonstrated using the SH_1 mode that when the mode impinges upon a sharp step down, most of the energy is converted to lower order modes. However when the slope of the thickness reduction was 0.46 mm per wavelength the SH_1 mode was completely reflected. Moreover, they demonstrated that a low order mode can convert to higher order modes when striking a sharp step up. Consequently if there is a source and a sensor on either side of a shallow sloped reduced thickness area as shown in Fig. 2(a) then only the guided wave modes that can propagate at the corresponding frequency thickness product at h_{min} will be detected by the sensor.

The effect of a thickness reduction with respect to the high order guided wave mode is similar to the effect of a low pass filter in signal processing. For example if h was 10 mm and h_{min} was 5 mm in an aluminium plate and a pure A_1 mode was excited by a source at 0.3 MHz, which corresponds to a frequency thickness product of 3 MHz mm, then the A_1 mode would not be detected by the sensor because its cutoff frequency thickness product is 1.56 MHz mm and the frequency thickness product at h_{min} is 1.5 MHz mm. This phenomenon is illustrated in Fig. 2(b). However if there were a sharp step up downstream of h_{min} then the A_1 mode could still be detected by the sensor because of mode conversion from A_0 back to A_1. Hence care will need to be taken when interpreting the signals received at the sensor.

The main limitation of this technique using a single mode is that it is only possible to determine whether the thickness is smaller or larger than a given value depending on whether the mode is detected or not. The method proposed in this paper is to improve the thickness resolution of the technique using a single model by using multiple high order guided wave modes simultaneously with different cutoff frequency thickness products. The SH modes are particularly interesting as they appear at regular intervals on the frequency thickness product axis (see Fig. 1(b)). The cutoff frequency of the higher order SH modes can be expressed as:

$$f_{cutoff} = V_s \frac{n}{2h} \tag{1}$$

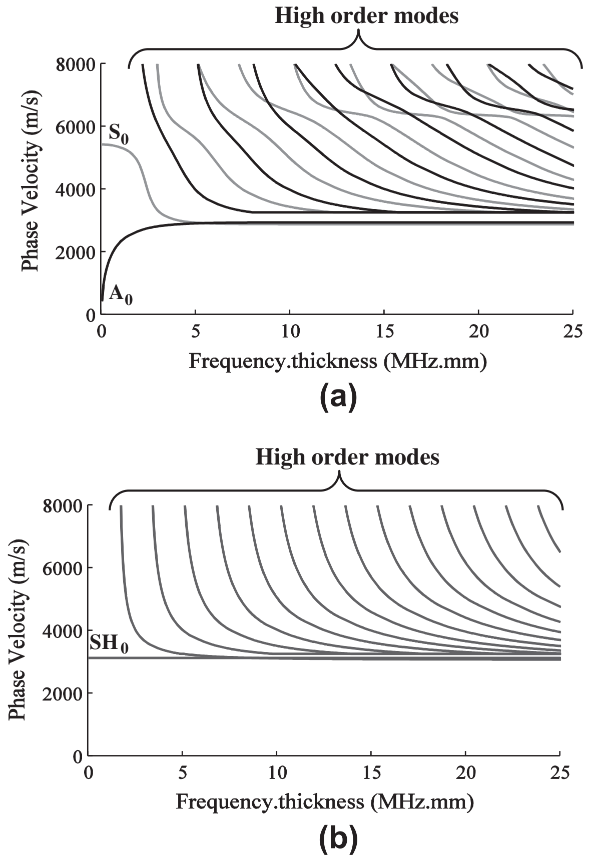

Fig. 1. (a) Lamb wave phase velocity dispersion curves in an aluminium plate (E = 70.8 GPa, ν = 0.34 and ρ = 2700 kg/m^3). The black solid lines correspond to the A_n modes, the light grey solid lines correspond to the S_n modes. (b) SH wave phase velocity dispersion curves in an aluminium plate.

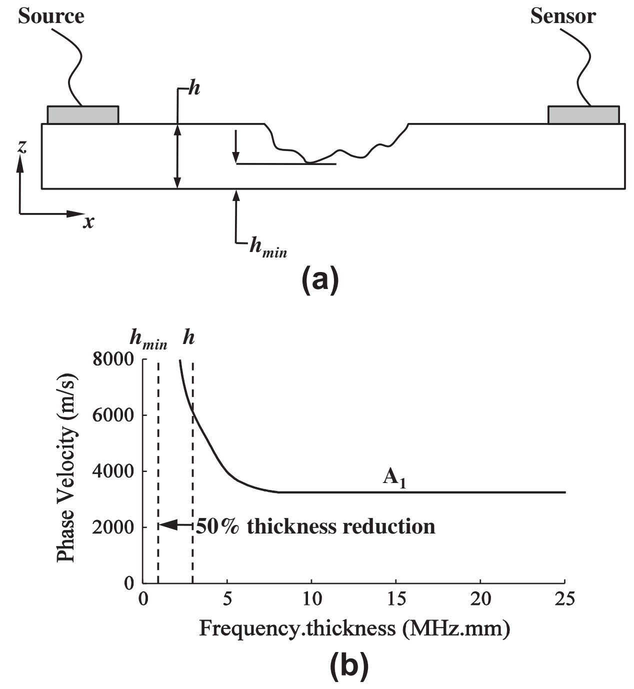

Fig. 2. (a) Source and sensor configuration to use the mode cutoff property to detect the minimum thickness h_{min} and (b) the phase velocity dispersion curve for the A_1 mode in an aluminium plate. The vertical dashed lines correspond to the frequency thickness product at h and h_{min} when the input signal is at 0.3 MHz in a 10 mm aluminium plate.