CHARACTERIZATION OF MATERIAL PROPERTIES IN MULTI-LAYERED TUBES

Yu-An Lai[1], Che-Hua Yang[2]

[1, 2]Department of Mechanical Engineering Chang Gung University, Tao-Yuan, Taiwan

Abstract

This research is focused on the characterization of material properties (MP) in multi-layered tubes. The proposed material characterization processes combines a theoretical model, an ultrasound measurement technique and an inversion algorism. A theoretical model based on a global matrix method is used to model the dispersion curves of longitudinal modes propagating in a tube with an arbitrary number of layers. A laser ultrasound technique (LUT) is used to measure dispersion curves of guided waves propagating in the tubes. An inversion calculation based on simplex algorism is used to determine the MP from the measured dispersion data. With this material characterization process, material properties, including elastic module and thicknesses for two-layered tubes, are determined and verified with independent measurements. Furthermore, the proposed characterization processes is used to characterize profiles of material properties in tubes which change their MP continuously across the thickness. The current result provides useful information for the application of nondestructive inspection of Zircaloy cladding tubes with hydride precipitation distributed across the thickness in an arbitrary way.

1. Introduction

There exists a widespread need for methodologies that can nondestructively evaluate cylinder. Many researchers have been interested in the application of guided wave for the inspection of tubes [1][2]. They have recognized the possibility for accurate, rapid and nondestructive inspection, such as gas, oil, and nuclear power generation [3][4]. The Zircaloy alloy is a popular tube material which forms the fuel cladding of nuclear power generation. The operations produce “hydrogen absorbed” in Zircaloy tubes. It will precipitate a layer of ZrH2 at the outer surface of Zircaloy tubes. It will influence the structure reliable in nuclear reactor.

The objective of the present study is to develop laser techniques in multi layered cylinder. To obtain the dispersion curve with LUT and inverse the material constant and geometric properties.

2. Theory

Guided wave in cylinder have three different kind mode, including longitudinal modes L(0,M), torsional modes T(0,M), and flexural modes F(n,M). Longitudinal and torsional modes are propagating with axially symmetric. Flexural modes are propagating with nonaxially symmetric.

For a isotropic, homogeneous material, the form of Navier’s equation of motion is:

$$m\nabla^2\mathbf{u} + (l + m)\nabla(\nabla\cdot\mathbf{u}) = r\frac{\partial^2\mathbf{u}}{\partial t^2} \tag{1}$$

Where $\boldsymbol{u}$ is the displacement field, l and m are the Lame constants of the material. r is the density. Substitution of the displacement u (2) into (1) results wave equation (3):

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

$$\nabla^2\Phi = \frac{1}{c_1^2}\frac{\partial^2\Phi}{\partial t^2}, c_1 = \sqrt{(l + 2m)/r} \tag{3-1}$$

$$\nabla^2 H_q - \frac{H_q}{r^2} = \frac{1}{c_2^2}\frac{\partial^2 H_q}{\partial t^2}, c_2 = \sqrt{m/r} \tag{3-2}$$

Where Eq.(3-1) and (3-2) represent the longitudinal wave motion and the shear wave motion. c1 and c2 are the longitudinal and shear wave velocities in the material.

Substitution Eq.(3) into Eq.(2) yield a solution to the displacement equation of motion with the unknown amplitude constants as Eq.(4)

$$\begin{aligned} u_r &= \left\{ \begin{array}{l} A_{(L+)}\left[-a H_1^1(ar)\right] + A_{(L-)}\left[-a H_1^2(ar)\right] \\ +A_{(S+)}\left[kH_1^1(br)\right] + A_{(S-)}\left[kH_1^2(br)\right] \end{array} \right\} e^{i(kz-wt)} \\ u_z &= \left\{ \begin{array}{l} A_{(L+)}\left[-kH_0^1(ar)\right] + A_{(L-)}\left[-kH_0^2(ar)\right] \\ +A_{(S+)}\left[-b H_0^1(br)\right] + A_{(S-)}\left[-b H_0^2(br)\right] \end{array} \right\} e^{i(kz-wt)} \end{aligned} \tag{4}$$

Using the strain-displacement and stress-strain relationship to obtain the stress (5) in the medium.

$$s_{rr} = m\begin{Bmatrix} A_{(L+)}\left[(k^2-b^2)H_0^1(ar)+2\frac{a}{r}H_1^1(ar)\right] \\ +A_{(L-)}\left[(k^2-b^2)H_0^2(ar)+2\frac{a}{r}H_1^2(ar)\right] \\ +A_{(S+)}\left[2kb\,H_0^1(br)-2\frac{k}{r}H_1^1(br)\right] \\ +A_{(S-)}\left[2kb\,H_0^2(br)-2\frac{k}{r}H_1^2(br)\right] \end{Bmatrix} e^{i(kz-wt)} \quad (5)$$

$$s_{rz} = m\begin{Bmatrix} A_{(L+)}\left[-2ka\,H_1^1(ar)\right] \\ +A_{(L-)}\left[-2ka\,H_1^2(ar)\right] \\ +A_{(S+)}\left[(k^2-b^2)H_1^1(br)\right] \\ +A_{(S-)}\left[(k^2-b^2)H_1^2(br)\right] \end{Bmatrix} e^{i(kz-wt)}$$

The boundary condition at the surface is assumed as traction free.

$$\begin{Bmatrix} s_{rr} \\ s_{rz} \end{Bmatrix} = 0 \quad (6)$$

The interfacial continuity condition at the interface of two layers is continuity of displacement, the normal and shear stress components. The boundary condition at the interface between arbitrary layers, i, and $(i+1)$ is:

$$\left[\Lambda_{i(i+1)}\right]\left[-\Lambda_{(i+1)(i+1)}\right]\begin{Bmatrix} A_i \\ A_{(i+1)} \end{Bmatrix} = 0 \quad (7)$$

The boundary condition for the inner and outer surface can be written as:

$$\begin{aligned} [\Gamma_{11}]\{A_1\} &= \{0\} \\ \left[\Gamma_{n(n+1)}\right]\{A_n\} &= \{0\} \end{aligned} \quad (8)$$

The global matrix □is obtained by combining all of the boundary condition. The form of the boundary condition of the arbitrary layered cylinder is:

$$[\Delta]\{A\} = 0 \quad (9)$$

In order to obtain the non-trivial solution of Eq.(9), the determinant of the global matrix Δ is set to zero. The dispersion relationship in the multilayer cylinder had obtained by solving this solution.

In this paper, the distribution of hydrogen can be continuous across the thickness with exponent. Alpha term (a) is an exponential coefficient in the cylinder. All material constant (E, n, r) is continual change along direction of radius according to alpha term in following equation:

$$x_i = x_0 + (x_n - x_0)\left(e^{a\frac{i}{n-1}} - 1\right)\Big/\left(e^a - 1\right) \quad (6)$$

3. Experiment and Inversion

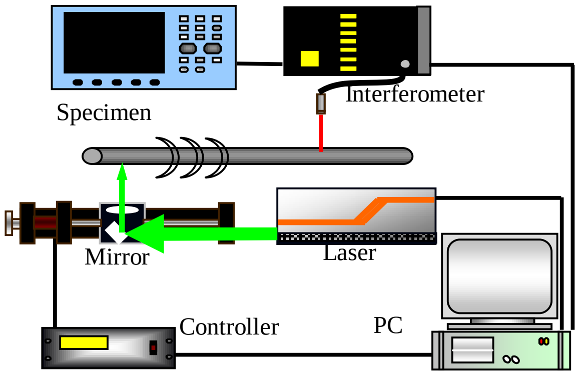

Figure 1: *Laser ultrasound measurement system.*

The measurements of guided wave are carried out with LUT and measurement system as shown in Fig.1. The pulsed Nd:YAG laser (Quantel YG780) is used for the generation of ultrasonic waves. The laser optical technique used for the detection of acoustic waves is a 3 mW interferometer (Polytec OFV 511). To measure the dispersion relation, a B-scan scheme is used. For the B-scan, the optical detector is located at the fixed location, while the generation laser beam is scanned toward the detector. A total scan distance of 10 mm, with a total number of 100 scanning steps in a step size of 0.1 mm, is used to obtain a set of dispersion curves.

A signal processing scheme using 2D FFT is used to extract multi-mode dispersion curves from the B-scan data. Finally, phase velocity versus frequency times plate-thickness (c-*fd*) are obtained.
To obtain the material constants and geometry parameters by comparing with the dispersion curve of experiment and theoretical modal and applying inversion technology (simplex [5] and golden section algorithm).

There are four kinds of specimen, including one layered brass cylinder (the thickness is 0.28 mm) and brass cylinder with aluminum coating (6 µm). The other are one layered steel cylinder (0.93 mm) and steel cylinder with copper coating (39 µm).

4. Results

4.1.1. Experiment and inversion

In one layer brass cylinder, the solid line and square in Fig.2 are the dispersion curve of experimental inversion and the result of LUT experiment. To compare Young's modulus of theory (100 GPa) with experimental inversion (106 GPa), the approximate error is 5 %. Fig. 3 is shown the experimental and inversive results of LUT on two layer brass cylinder with aluminum coating (6 μm). The inversive coating thickness is 9 μm.

In one layer steel cylinder, the solid line and circle in Fig.4 are the dispersion curve of experimental inversion and the result of LUT experiment. To Compare material constant of theory with experimental inversion, error is small than 5 %. The dash line and triangle are the inversive and experimental result in two layers steel cylinders with copper coating. The coating thickness is 41 μm using inversion. The approximate error is 5 % comparing the inversion with the real thickness of coating is 39 μm.

4.1.2. Numerical calculation

In numerical calculation, the distribution of hydrogen is discussed. Fig.5 is the dispersion curves of zircaloy tubes have different alpha term. Obviously, at same frequency, phase velocity is bigger with bigger alpha. For L(0, 2) mode, at frequency of 3 MHz, the approximate phase velocity shifting is 1 Km/sec with alpha from -10 to 10 in Fig. 6.

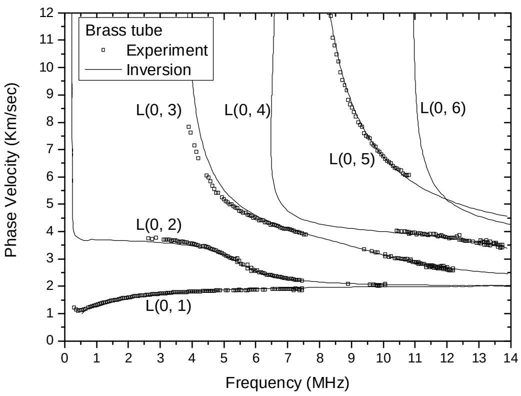

Figure 2*: Experimental and inversive results of LUT on one layer brass cylinder.*

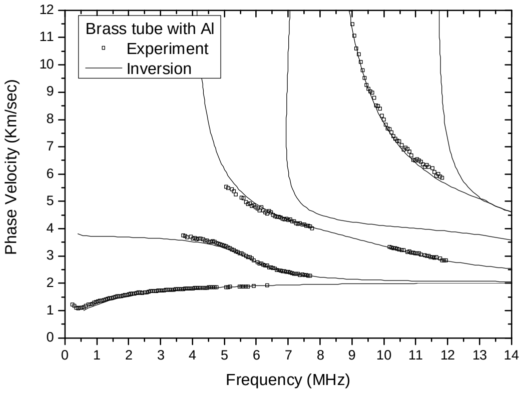

Figure 3*: Experimental and inversive results of LUT on two layer brass cylinder with aluminum coating.*

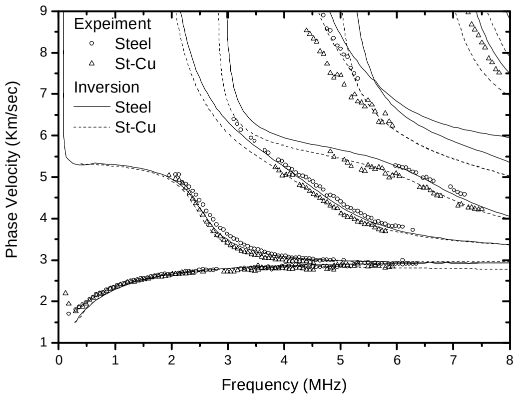

Figure 4*: Experimental and inversive result of LUT in one layer steel cylinder and two layer steel cylinder with copper coating.*

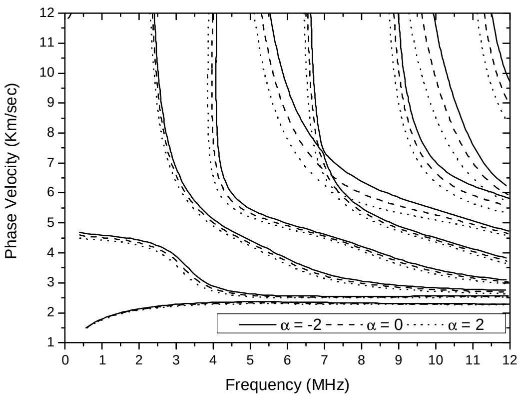

Figure 5*: The dispersion curves of Zircaloy tubes have different distribution of hydrogen*

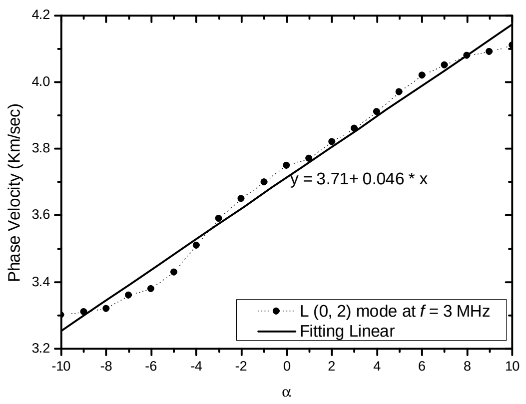

Figure 6: *Velocity shifting in the Zircaloy tubes have different distribution of hydrogen*

5. Conclusions

This paper demonstrates the effectiveness of using LUT to study the propagation of guided waves in multilayered cylinders. Also, successful development on the calculating the dispersion curves of guided modes propagating. On the development of characterizing inhomogeneous hydride precipitation in Zircaloy claddings. Dispersion of guided modes for tubes with Inhomogeneous material properties across the thickness with arbitrary profiles can be calculated, exponential distribution for example. Geometry properties of steel can be obtained with (LUT +Simplex) method for steel tube with copper coating, and there is good agreement.

6. References

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