Available online at www.sciencedirect.com

ScienceDirect

Ultrasonics 46 (2007) 74–88

Ultrasonics

www.elsevier.com/locate/ultras

A combined finite element and modal decomposition method to study the interaction of Lamb modes with micro-defects

N. Terrien [a,*], D. Osmont [a], D. Royer [b], F. Lepoutre [a], A. Déom [a]

[a] *ONERA, Structures and Damage Mechanics Department, BP 72, 92322 Châtillon, France*
[b] *Laboratoire Ondes et Acoustique, ESPCI, 10 Rue Vauquelin, 75231 Paris Cedex 05, France*

Received 21 June 2006; received in revised form 9 November 2006; accepted 11 November 2006
Available online 14 December 2006

Abstract

This paper presents a combined finite element and modal decomposition method to study the interaction of Lamb waves with damaged area. The finite element mesh is used to describe the region around the defects. On the contrary to other hybrid models already developed, the interaction between Lamb waves and defects is computed in the temporal domain. Then, the modal decomposition method permits to determine the wave reflected and transmitted by the damaged area. Modal analysis allows also identifying the mode conversions induced by the defects. These numerical results agree with previous finite element results concerning the interaction of Lamb modes with a notch. Experiments, carried out with gauged defects on an aluminum plate, are also compared to numerical predictions to validate the simulation. Compared to classical techniques of simulation, this new method allows us to investigate the interaction of Lamb modes generated at high frequency-thickness product with micro-defects as corrosion pitting.

PACS: 43.20.+g; 43.58.+z

Keywords: Lamb waves; Micro-defects; Interactions; Simulations; Finite element; Modal decomposition

1. Introduction

Many authors have already investigated the interaction of Lamb modes with a single defect like crack, notch or circular cavity. Some of them used analytical [1] or semi-analytical [2] resolutions, whereas others chose a finite element or a boundary element modeling [3–6]. Analytical or semi-analytical resolutions can be used when the geometry of the defect is regular and when the problem presents symmetries. Finite or boundary element modeling allows studying the interaction of Lamb modes with irregular defects but require to respect spatial and temporal discretization which can cause numerical problems at high frequency-thickness product. Indeed, the number of freedom degrees of this problem becomes rapidly huge and cannot be solved only by using a finite element model.

To investigate the interaction of Lamb modes with micro-defects, we propose a simulation combining a finite element approach and a modal decomposition method. The finite element mesh is used to describe the region around the defects. This method has the advantage that defects can be quite arbitrary in terms of geometries, size and quantities. To minimize the numerical size of the problem and thus the time of computing, a modal decomposition of the wave calculated before and after the defect, is performed. This decomposition allows us to decrease the length of the meshing plate and facilitates the interpretation of the waveform calculated as the superposition of different Lamb modes diffracted by the defects.

Even if the purpose of our modeling (to extract the modes converted by defects) is similar to approaches already developed by other authors [7–12], the method

* Corresponding author. Tel.: +33 1 46 73 46 87; fax: +33 1 46 73 48 91.
E-mail address: terrien@onera.fr (N. Terrien).

0041-624X/$ - see front matter
doi:10.1016/j.ultras.2006.11.001

itself is quite different. These authors combined a finite element method and a modal decomposition to investigate the interaction of Lamb waves with defects in the frequency domain. Then the problem has to be solved for each frequency of the excitation bandwidth. In this paper, we investigate the interaction of Lamb waves with defects in the temporal domain with an available finite element software "Zebulon" developed by ONERA. Then, displacements and stresses are picked up along the thickness of the plate to decompose the wave transmitted by the damaged area on the Lamb waves basis. So, the identification of the different propagating Lamb modes via the modal decomposition leads to a decrease of the length of the mesh. Compared to the contribution of Alleyne and Cawley [4] who used a pure finite-element method combined with a 2D-Fourier transform technique for extracting mode conversions, our method allows us to mesh a plate of approximately a third of the length of the mesh used in the model of Alleyne and Cawley. Our method permits to compute more efficiently the interaction of Lamb waves with defects but also to investigate the interaction of higher frequency Lamb modes with smaller defects such as corrosion pitting of 100-μm depth. Such a problem cannot be solved only with an usual finite element modeling because of the dimension of the necessary meshing plate that requires too much memory.

2. Numerical simulation

The hybrid method proposed in this part is divided into three main steps: the finite element modeling, the modal decomposition method and the analytical propagation of Lamb waves.

2.1. Finite element model

This simulation is based on the finite element method and includes an explicit algorithm for solving the transient wave propagation. The plate is considered as infinite in the x_3-direction so that a plain strain condition is used (Fig. 1). The mesh size must be able to represent the physical characteristics of the wave propagation. First, the smallest wavelength $\lambda_{\min}$ must be correctly sampled to describe the propagating mode in the frequency range of investigation. The spatial discretization δx_1 and δx_2 of each element of the mesh satisfies the condition:

$$\max(\delta x_1, \delta x_2) < \frac{\lambda_{\min}}{10}. \tag{1}$$

Moreover, the mesh must be able to describe the geometry of the problem. Thus, small defects such as cavities or notches are usually described with more than six nodes. It is the reason why the density of elements increases close to a defect area whereas the mesh is larger elsewhere (Fig. 1). Another stability condition is that the time step must be chosen so that no wave can propagate across one mesh spacing in less than one time step. Typically, the time discretization must verify the condition:

$$\delta t < 0.7\frac{\min(\delta x_1, \delta x_2)}{V_{\mathrm{L}}} \tag{2}$$

where V_{L} is the longitudinal wave velocity.

To generate the appropriate pure Lamb mode in the structure, boundary conditions are imposed on the left edge of the plate. Its displacement normalized by the power flow through the plate thickness (equal to 1 W/m) is applied on the left edge of the plate (Fig. 2b). To simulate the time profile of the excitation, this spatial distribution is multiplied by a 10-cycle tone burst enclosed in a Hanning window centered on the excitation frequency (Fig. 2c). The plate length is defined to prevent that reflections from the edges of the mesh disturb the analysis of the calculated waveforms and is minimized to reduce the computing time. Series of nodes through the thickness of the plate are monitored along vertical lines located on the left and on the right of the damaged region (Fig. 2a).

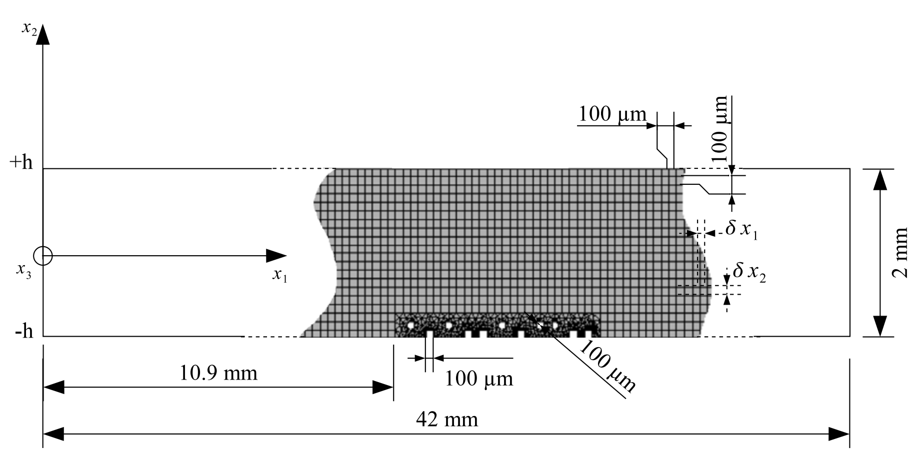

Fig. 1. Illustration of finite element spatial discretization and mesh refinement around defects. Notches and cavities simulate corrosion pitting.