Ultrasonics 73 (2017) 187–195

Contents lists available at ScienceDirect

Ultrasonics

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

Guided wave scattering by geometrical change or damage: Application to characterization of fatigue crack and machined notch

Nicolas Quaegebeur *, Nidhal Bouslama, Maxime Bilodeau, Robin Guitel, Patrice Masson, Ahmed Maslouhi, Philippe Micheau

GAUS, Dept. of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, QC J1K2R1, Canada

ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form 12 September 2016
Accepted 12 September 2016
Available online 14 September 2016

Keywords:
Guided waves
Diffraction
Scattering
Far-field
Crack
Piezoceramics

ABSTRACT

Validation of guided-wave based systems for Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) under realistic conditions or environment requires complex setups. For this purpose, numerical or theoretical approaches are useful to save time and cost associated with experiential tests. However, the interaction with realistic geometrical (rivets, thickness changes, stiffeners, extrusions) or damage features (fatigue cracks, fillet cracks, delaminations, disbonds) must be accurately captured in order to be representative. In this paper, an experimental methodology is presented for estimating the far-field scattering of geometrical or damage features. The principle is based on the use of a Hankel transform of the measured 3D velocity field in order to evaluate with precision and repeatability the scattered pattern using a spatially averaged method. Application to scattering of a hole with simulated machined and real fatigue cracks is proposed. It is observed that the simulated machined crack generally used as a reference standard can only model accurately the transmission behaviour while the scattering patterns are only similar when the wavelength is about the size of the crack, limiting the practical use of machined cracks for experimental validation of SHM or NDE systems.

1. Introduction

Validation and design of guided-wave based systems for Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) under realistic conditions or environments requires complex setups [1,2]. For this purpose, numerical or theoretical approaches are useful to save time and cost associated with experiential tests. However, the interaction with realistic geometrical (rivets, thickness changes, stiffeners, extrusions) or damage features (fatigue or fillet cracks, delaminations, disbonds) must be accurately characterized in order to be representative. Moreover, recent approaches in damage imaging [3–6] benefit from the consideration of scattering patterns in order to improve damage sensitivity and reduce localization errors. Under those circumstances, a need for numerical or experimental validation of damage scattering is required.

In the case of simple geometrical features such as surface cracks [7], through the thickness cracks [8–10], flat bottom holes [11] or thickness changes [12], 2-D analytical models of the guided wave interaction have been proposed, but only allow taking into account the transmission and reflection at the geometrical feature of interest following the plane strain assumption. In order to cover the scattering of geometrical features such as rivets, holes or discontinuities, a 3-D model is required but due to the complexity of the problem, plate models (flexural waves under the Mindlin theory [13]) have been first proposed [14]. More recently, the extension to complex mode conversion, symmetrical, Shear-Horizontal (SH) or higher order modes has been considered using Lamb wave theory [15,16]. In the case of more complex 3-D geometrical or damage features, numerical methods, such as Finite Element Models (FEM) or Boundary Element Models (BEM) are required, with the ability to conform to complex geometries, such as delamination spreading in composites [17,18], closed [19] or semi-open cracks [20,9,21]. Those methods are very powerful, as well as time-consuming in order to cover the desired incidence angles and frequency ranges. Moreover, in the case of realistic damage, the classical models used for static or stress concentration analysis (node separation) must be validated experimentally in both transmission, reflection and scattering.

For this purpose, some experimental studies have been proposed to estimate the far-field scattering of typical damage features. Usually, contact or non-contact sensors such as angled wedges [22,23] or Laser Doppler Vibrometer (LDV) [24] are used for measurement and bonded piezoceramics [25] or contact transducers are used for guided wave generation. In the case of

* Corresponding author.
E-mail address: nicolas.quaegebeur@usherbrooke.ca (N. Quaegebeur).

http://dx.doi.org/10.1016/j.ultras.2016.09.014
0041-624X/© 2016 Elsevier B.V. All rights reserved.

bulk-wave generation, numerical analysis and contact measurement at high frequencies have also been used to compute the scattering coefficient matrix [26] based on spatially averaged amplitude measurement of the scattered field.

To our knowledge, time-domain measurements over a limited bandwidth (burst signals) have been proposed as the best solution to separate incident and scattered fields, such that experimental limitations in terms of frequency range (typically below 100 kHz) and experimental setup dimensions are observed. In the case of numerical simulations or when the structure is gradually damaged, baseline subtraction is also required to estimate properly the scattered field and remove the incident wave packet [26]. Furthermore, the problem of attenuation (wave spreading) with respect to the propagation distance impairs the estimation of the scattering pattern and thus a compensation strategy is required [25]. More recently, a spatial Fourier transform approach has been proposed for scattering analysis in composite structures [27,28], but this is limited to the analysis of the transmission and reflection coefficients under plane wave assumption and scattering effects can hardly be compared between different structures. Under those circumstances, the sensitivity, precision and repeatability of the existing approaches have not been studied in details, such that the comparison between different structures cannot be carried out convincingly.

In this paper, an experimental methodology is presented for estimating the far-field scattering of geometrical or damage features. The principle is based on the use of a Hankel transform of the measured 3-D velocity far-field in order to evaluate with high precision and repeatability the scattering pattern in the frequency domain using a spatially averaged method. This allows for spatial averaging, noise reduction, incident field rejection, mode selection and separation which was not proposed in the previous approaches [26,25]. Application to the scattering of a hole with machined discontinuities and real fatigue cracks is proposed. Section 2 introduces the principle of the far-field scattering estimation. Section 3 is dedicated to the experimental implementation and limitations of the approach with respect to the structure of interest. Section 4 proposes a simple repeatability analysis and the experimental comparison of scattering between fatigue and machined cracks.

2. Far-field directivity estimation

In the present paper, the interaction of guided waves with a geometrical feature is considered as presented in Fig. 1. Neglecting the plate edge reflections, any component of the surface displacement field $u(r,\phi,\omega)$, described in the frequency domain at angular frequency ω and depending on the polar coordinates (r,ϕ) can be expressed in the whole structure as the summation of the incident $u_i(r,\phi,\omega)$ and scattered $u_d(r,\phi,\omega)$ wave fields [14,29]:

$$u(r,\phi,\omega) = u_i(r,\phi,\omega) + u_d(r,\phi,\omega) \tag{1}$$

The purpose of the present paper is thus to estimate the scattered field as a function of polar angle ϕ for a given incident wave defined by its incidence direction ϕ_{inc}, also defined as the scattering coefficient matrix [26].

In the following section, a method to extract the far-field scattering based on integral transform is proposed. The idea is to perform a series of measurements of surface velocity (in-plane and out-of plane) using a 3D Laser Doppler Vibrometer (3D-LDV) over a cylindrical grid of points as described in Fig. 1 in order to achieve a mode selective and spatially averaged estimation.

2.1. Scattered wave characterization

Without loss of generality, the scattered field $u_d(r,\phi,\omega)$ can be expressed in the frequency domain using cylindrical harmonics as an infinite sum of propagative and evanescent waves [29]:

$$u_d(r,\phi,\omega) = \sum_{n=0}^{\infty}\left(C_n^m(\omega)H_n^{(1)}(k_m r) + D_n^m(\omega)K_n(k_m r)\right)e^{jn\phi} \tag{2}$$

where $H_n^{(1)}$ denotes the Hankel function of first kind and nth order, K_n denotes the modified Bessel function of the second kind and nth order, $C_n^m(\omega)$ and $D_n^m(\omega)$ represents the amplitude of the nth cylindrical harmonics for propagating and near-field components respectively and k_m denotes the wavenumber associated with propagating mode m. Single mode propagation is assumed in the following formulation for clarity but the linearity of the problem allows the displacement field to be defined as the summation of the contributions of each mode. The far-field scattered field $F_m(\phi,\omega)$ associated with mode m is obtained by considering the evolution of Eq. (2) when $r \to \infty$ [30]:

$$u_d(r,\phi,\omega) = H_0^{(1)}(k_m r)F_m(\phi,\omega) + \mathcal{O}\left(\frac{1}{\sqrt{k_m r}}\right) \tag{3}$$

where $\mathcal{O}$ is the big O notation defining the asymptotic growth rate of the diffracted field for large value or r, and:

$$F_m(\phi,\omega) = \sum_{n=0}^{\infty}(-j)^n C_n^m(\omega)e^{jn\phi} \tag{4}$$

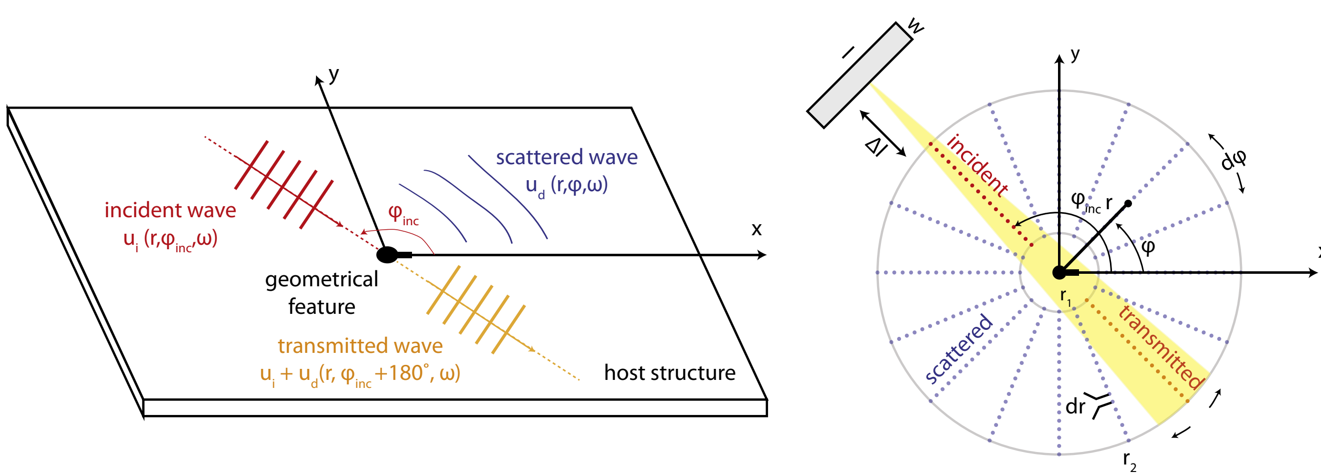

Fig. 1. Presentation of the incident, scattered and transmitted wave fields (left). Configuration for scattering characterization (right).