Journal of Sound and Vibration 394 (2017) 515–526

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Time reversal invariance for a one-dimensional model of contact acoustic nonlinearity

Philippe Blanloeuil [a,*], L.R. Francis Rose [a], Martin Veidt [b], Chun H. Wang [c]

[a] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia
[b] School of Mechanical & Mining Engineering, University of Queensland, Brisbane, QLD 4072, Australia
[c] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney NSW 2052, Australia

ARTICLE INFO

Article history:
Received 13 October 2016
Received in revised form
27 January 2017
Accepted 31 January 2017
Handling editor: L. G. Tham
Available online 10 February 2017

Keywords:
Contact acoustic nonlinearity
Time reversal invariance
Finite difference method

ABSTRACT

The interaction of a one-dimensional (1D) wave packet with a contact interface characterized by a unilateral contact law is investigated analytically and through a finite difference model. It is shown that this interaction leads to the generation of higher harmonic, sub-harmonic and zero-frequency components in the reflected wave, resulting in a pulse distortion that is attributable to contact acoustic nonlinearity. However, the results also show that the re-emission of a time reversed version of this distorted first reflection results in a healing of the distortions and a perfect recovery of the original pulse shape, thereby demonstrating time reversal invariance for this type of contact acoustic nonlinearity. A step-by-step analysis of the contact interaction provides insights into both the distortion arising from the first interaction and the subsequent healing during the second interaction. These findings suggest that time reversal invariance should also apply more generally for scatterers exhibiting non-dissipative contact acoustic nonlinearity.

1. Introduction

The application of nonlinear acoustics for nondestructive evaluation and structural health monitoring has attracted considerable research interest over the past two decades, driven by the prospect that various forms of structural damage may induce a nonlinear response that could lead to earlier damage detection than would be possible through conventional linear ultrasonics [1–3]. It is pertinent to distinguish between cases where the structural damage (and hence the source of nonlinearity) is more-or-less uniformly distributed throughout the structure, so that the response can be adequately modelled by an appropriate nonlinear constitutive equation for the material [4–6], and cases where the damage is localized, with the surrounding material behaving linearly. The present work is concerned with the latter case. In practice, two important forms of localized damage are fatigue cracks in structural alloys and delaminations in composite laminates. For both of cases, the nonlinear response can generally be attributed to contact acoustic nonlinearity (CAN) [7–15], which induces the generation of new frequency components such as higher harmonics, sub-harmonics and zero frequency (DC) response. The mechanisms involved in CAN include clapping between the contacting interfaces [7,9], as well as dissipative mechanisms due to frictional sliding [8,12]. Theoretical models of varying levels of sophistication have been proposed for all of these mechanisms, as comprehensively reviewed in [14]. We note in particular the recent work on the vibrational response of

* Corresponding author.
E-mail address: philippe.blanloeuil@rmit.edu.au (P. Blanloeuil).

http://dx.doi.org/10.1016/j.jsv.2017.01.050
0022-460X/

beams with breathing cracks [15–18], of plates with delaminations [19,20], as well as wave scattering by cracks and delaminations [21–25] as examples of the current state of the art for CAN modelling.

The time reversal (TR) method [26–28] allows one to reconstruct a source signal at the excitation point from signals recorded and reemitted at some measurement points away from the source, after being reversed in time. This reversibility is based on the spatial reciprocity and time invariance of the linear wave equation, and is referred to as TR invariance. This property has been successfully exploited to derive various TR techniques for detecting and imaging structural damage through a wide variety of distinct approaches [29–42]. The TR invariance has been demonstrated in various propagation media and holds for linear scatterers as amply demonstrated by Fink et al [26,28,43], and hence for damage that can be modelled as linear scatterers, e.g. corrosion thinning or open cracks. TR invariance has also been verified for classical material nonlinearity as long as the propagation distance is shorter than the shock formation distance [44]. In that case, the wave form is progressively recovered during the back propagation and the distortions accumulated during the initial propagation are cancelled.

However, to the best of our knowledge, the issue of time reversal invariance in the presence of CAN at a localized nonlinear defect has not been investigated previously. It can be expected on physical grounds that time reversal invariance will not hold in the presence of dissipative mechanisms such as frictional sliding, but it is not immediately obvious whether or not this invariance may still hold for frictionless contact that can generate nonlinear responses such as pure clapping at the contact interface. This is addressed in the present work. Of particular relevance regarding the present work is the suggestion by Sohn et al. [45,46] that the nonlinearity induced by the presence of damage would result in a breakdown of TR invariance, and therefore experimental observation of a breakdown could serve as a baseline-free diagnostic for detecting damage [47]. However, considering the spectral enrichment due to CAN, it is not clear whether the TR breakdown is attributable to the nonlinear nature of the defect, or to the limited bandwidth of the sensors and their inability to capture the full range of frequency information. Accordingly, a numerical modelling is employed here in order to investigate the TR process solely associated with CAN without any possible bandwidth limitations of practical sensors and actuators.

A simplified one-dimensional (1D) model of CAN is considered in this work, whereby a longitudinal wave packet interacts with a contact interface between the propagation medium and a rigid boundary acting as a limiter. A similar configuration has recently been used to model the vibrational response of a rod with a breathing crack in [48]. CAN is modelled here with a unilateral contact law, which correctly captures the dynamics of normal impacts between contacting surfaces associated with clapping. A time explicit finite differences (FD) scheme is used to solve the propagation problem. The presentation is organized as follows. The configuration and governing equations are presented in Section 2, as well as an analytical representation for the incident and reflected wave field. A computational approach based on finite difference approximations is outlined in Section 3. Detailed results are presented in Section 4, and Section 5 provides concluding remarks as well as indications for future work.

2. Formulation of a 1D propagation model with CAN

A semi-infinite isotropic and homogeneous medium in contact with a rigid plane is considered as shown in Fig. 1. The material is steel, with Young's modulus $E = 210$ GPa, Poisson's coefficient $\nu = 0.3$ and density $\rho = 7800$ kg/m^3. A longitudinal wave packet (or tone burst) is generated at $x = 0$ mm and propagates along the x-axis. Under these conditions, a 1D propagation model can be adopted. The contact interface is made with the rigid plane located at $x = L$. A pre-existing compressive stress state $\sigma_0 \leq 0$ is considered to exist at the contact interface. The incident wave packet propagates and interacts with the contact interface, and the reflected wave contains new frequency components due to CAN. Additionally, a transparent boundary is considered at $x = 0$ mm, so that the wave travelling back from the contact interface is not reflected at $x = 0$ mm.

The 1D wave equation is given by:

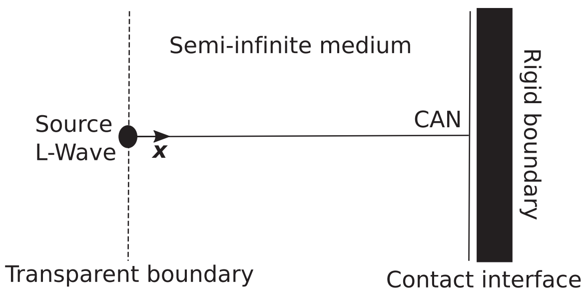

Fig. 1. 1D model configuration. A plane wave is propagating in a semi-infinite medium. The solid is in contact with a rigid boundary where contact laws are considered to model CAN. The reflected wave contains higher harmonics due to CAN.