Damage Detection of Defects Using Linear and Nonlinear Guided Waves

Thesis submitted

in fulfilment of the requirements for the degree of

Doctor of Philosophy

by Reza Soleimanpour

Faculty of Engineering, Computer and Mathematical Sciences

School of Civil, Environmental and Mining Engineering

The University of Adelaide, North Terrace Campus

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A_0	Signal amplitudes at reference point
$A(\Delta x)$	Signal amplitudes at distance Δx away from the reference point
A_n	Amplitude of the *n*-th harmonic
c_L	Longitudinal wave speed
c_g	Group velocity of the wave packet
$c_g(f_c)$	Group velocity of the incident A_0 guided wave at the excitation frequency f_c
$c_g(2f_c)$	Group velocity of the second harmonic guided wave
c_p	Phase velocity of the wave packet
d	delamination size
d_{a-r}	Distance between the actuator and receiver
d_{d-r}	Distance between the delamination and the receiver
d_{a-d}	Distance between the actuator and delamination
$D_s^{(r,\theta)}$	Out-of-plane displacement of the scattered wave
$D_d^{(r,\theta)}$	Out-of-plane displacement in the damaged model
$D_i^{(r,\theta)}$	Out-of-plane displacement in the intact model
E	Young's modulus
E^{II}	Intact material second-order linear elasticity
f_c, f	Excitation frequency
h	Overclosure

$H(\varepsilon)$	Heaviside unit
k	Wavenumber
k_i	Attenuation coefficient
L_{min}	Smallest mesh size
l_e	Maximum mesh size
p	Contact pressure
p^*, q	Wavelet transform factors
t_{f_c}	Incident wave packet arrival time
t_{2f_c}	Second harmonic wave packet arrival time
$u(t)$	Out-of-plane displacement of the guided wave signal
$w_s(t)$	Scattered wave data
$w_b(t)$	Baseline wave packet data
$w_t(t)$	Total wave packet data
$\widehat{w_s}(f_c)$	Scattered wave packet data in frequency domain
$\widehat{w_t}(f_c)$	Total wave packet data in frequency domain
$\widehat{w_s}(2f_c)$	Second harmonics scattered wave packet data in frequency domain
α_ω	Mass proportional Rayleigh damping constant
β_ω	Stiffness proportional Rayleigh damping constant
Δt	Time increment
Δx	Distance between two measurement points

$\Delta\phi$	Phase change
$\Delta\tau$	Normalized modulation pulse length
ε	strain
ε^0	Initial static contact strain
λ_{min}	Minimum wavelength size
υ	Poison’s ratio
$\delta\prod^c$	Contact virtual work contribution
ρ	Density
σ	Stress
$\chi(t)$	Mother wavelet
ω	Angular central frequency

Statement

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due The University of Adelaide - 2013 Program Rules Adelaide Graduate Centre 41 reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree. I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968. The author acknowledges that copyright of published works contained within this thesis resides with the copyright holder(s) of those works. I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library catalogue and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

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Abstract

In the past few years, application of guided waves for damage detection has been a topic of significant interest for many studies. Conventional guided wave techniques have been widely used in industry and technology for material characterisation and quality assessment by making use of so called linear acoustic response of material. It generally results in modification of linear parameters of guided waves such as wave amplitude, wave velocity, wave mode, and wave reflection and transmission. However, conventional guided wave techniques rely on baseline data known as the major linear guided wave techniques culprit. Among all guided wave techniques, nonlinear guided wave has been known as a promising baseline free approach, which offers enhanced reliability and practicability for damage detection. However, understanding of nonlinear guided waves is of essential importance for detecting and localising defects in structures. The nonlinear approach to acoustic non-destructive testing (NDT) is concerned with nonlinear responses of the guided waves, which is inherently related to the frequency changes of the input signal.

Nowadays, composite materials are widely used in structures due to their attractive properties such as higher stiffness to mass ratio and better corrosion resistance compared to metals. So far, most of studies on application of nonlinear guided waves have been dedicated to isotropic materials, such as aluminium and steel, whereas only a limited number of works have been carried out on application of nonlinear guided waves in anisotropic materials. Moreover, most of works in this area have focussed on classical nonlinearity raised from material nonlinearity whereas a limited number of researches have focused on non-classical nonlinearity raised from contact acoustic nonlinearity (CAN).

This research deals with linear and non-classical nonlinear interaction of guided waves with defects in structures from both numerical and experimental prospective. The aim of this research is to investigate guided waves for damage detection and damage localisation by developing an advanced 3D explicit finite element model for predicting the interaction of

guided waves with defects in isotropic and anisotropic material. The study first focuses on linear guided waves for damage detection and is expanded to nonlinear guided waves. Chapters 3 and 4 focus on linear guided waves whereas Chapters 5 and 6 focus on nonlinear guided waves. The numerical work has been carried by an advanced 3D explicit finite element code in ABAQUS v6.14. Verification of finite element models has been carried out by comprehensive experimental studies. The linear guided wave measurement has been carried out using high precision scanning laser Doppler vibrometer (Polytec PSV-400-3D-M) and nonlinear guided waves measurement has been captured using a computer controlled arbitrary waveform generator (NI PXI-5412) and a NI PXI-5105 digitizer. The data has been processed in time domain and frequency domain and time-frequency domain using Matlab.

The results of this study provide an improved physical insight into linear and nonlinear guided waves techniques. The results show that guided waves can be used for detecting and locating damages in beams and plates. However, nonlinear guided wave technique is a better option as it does not rely on baseline data and is more sensitive to small damages than the linear guided waves. A nonlinear guided wave damage localisation technique is introduced in this study which can accurately detect and locate damages without relying on baseline data.