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One-dimensional time-domain finite-element modelling of nonlinear wave propagation for non-destructive evaluation

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ABSTRACT

This one-dimensional time-domain finite-element model achieves accurate quantitative modelling of ultrasonic wave propagation in multi-layered structures. First, a sinusoidal wave toneburst is sent into a single layer of material exhibiting inherent material nonlinearity characterised by the nonlinear parameter β and thick enough for the toneburst received in through transmission to be resolved. The signal processing protocol that yields the theoretically correct quantitative value of β involves measuring the received toneburst for several propagation distances as well as the use of scaling factors taking into account the fast Fourier transform implementation, input signal windowing and material damping. Using that model configuration, model parameters (element size, time step, frequency step, input pressure, etc.) are then optimised and chosen quantitatively to generate accurate results. Finally, these model parameters are used for cases of interest where the configuration is not such that the exact β value can be obtained – e.g. thinner sample, pulse-echo etc. but where confidence in the results remains. This quantitative model that can be used for multi-layered structures provides a tangible resource useful to NDE engineers: a new prediction tool expected to enable them to choose the experimental set-up, driving frequency and post-processing method that would optimise kissing bond detection capability.

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1. Introduction

The use of nonlinear ultrasonic behaviour in non-destructive evaluation (NDE) is an approach shown to be sensitive to very small defects such as distributed micro-cracking [1,2] and small delaminations in composites [3,4], fatigue, thermal and chemical damage [5] as well as other contact type defects [6] including tight cracks, disbonds and weakening of adhesive bonds [7–12]. Nonlinear ultrasonics has therefore already been used in NDE as a tool for material characterisation [13–16], for damage detection looking at the internal microstructural properties of materials [3] and for assessing the quality of adhesive bonds [7,11,12] where nonlinear binding forces cause a nonlinear modulation of transmitted or reflected ultrasonic waves [9].

With advantages such as weight saving and higher fatigue strength, adhesive bonding is increasingly being used in the automotive and aerospace industries. There is therefore a real need to identify the boundary imperfections that lead to adhesion failure. But while the detection of finite thickness disbonds generally presents few problems, zero-volume disbonds or kissing bonds [17] are extremely difficult to detect and might benefit from the use of nonlinear ultrasonics. It has been shown that such imperfect interfaces introduce a higher degree of nonlinearity as a result of contact acoustic nonlinearity (CAN) [1,18]. When an ultrasonic wave interacts with such a defect, it is distorted, and this distortion can be used to detect the presence of a kissing bond [18–21] or obtain information on the adhesive bond strength [10].

In Richardson's model [22], the level of nonlinearity is explained by the intermittent opening and closing of the gap. Biwa's [18] theoretical analysis for the nonlinear behaviour of elastic waves propagating through a contact interface is commonly referred to. Yan [19] carried out similar experimental work on aluminium blocks [20] that looked promising. However, experimental results obtained on multi-layered structures like adhesive joints were not conclusive [8,9] and underline the challenges when carrying out such nonlinear measurements – either the harmonic generation is small with the harmonics sitting barely above noise level, or the acoustic power required to generate nonlinear effects introduces instrumentation nonlinearities and/or significant new damage [23]. This likely explains the difficulty the nonlinear ultrasonics community has had in making such a scheme operational.

Numerical models have been developed to simulate wave propagation through a nonlinear interface but only between homogeneous and linear solids like in the case of a crack [24].

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Spring models have been used to measure the ultrasonic response from imperfect solid–solid contact interfaces [24,9,18] and spring-mass models [21,25] when taking into account changes in density due to pores or inclusions at the interface.

However, very little work has been done on wave propagation in multi-layered structures with both linear and nonlinear interfaces, made up of various materials exhibiting some degree of inherent nonlinearity. Furthermore, no theoretical predictive studies exist for accurate quantitative modelling.

The authors have therefore developed a generalised quantitative one-dimensional (1-D) finite-element (FE) type model for simulating nonlinear ultrasonic wave propagation in such structures. In the current paper, the foundations of this model are presented by looking at single-layer structures. The purpose of developing such a model is to provide not only a better understanding of nonlinear wave propagation in multi-layered structures but also a tangible resource useful to NDE engineers: a new prediction tool expected to enable them to choose the experimental set-up, driving frequency and post-processing method that would optimise kissing bond detection capability.

Section 2 describes the theoretical basis of the method and the mathematical description of the model. However, the nonlinear phenomenon of interest is so weak that its accurate simulation is potentially compromised by different parameters. This is the reason why even such a simple FE model needs detailed investigation and refinement in order to obtain correct results. The modelling guidelines that ensure the model's accuracy are therefore given in Section 3. Example results for longitudinal wave propagation in nonlinear materials are presented in Section 4.

It should be noted that the same capability now exists in commercial packages such as the Comsol Multiphysics but here the authors are trying to provide practical guidelines for FE users since this is a relatively immature field.

2. Model development

2.1. Theory

The derivation of the nonlinear ultrasonic wave equation can be found in numerous works [8,26] and in this paper, the standard approach described by Meurer in [27] was followed. In this 1-D problem, the nonlinear equation for longitudinal waves in damped isotropic materials can therefore be written as

$$\rho\frac{\partial^2 u}{\partial t^2}=\left[K_2-\beta K_2\frac{\partial u}{\partial x}\right]\frac{\partial^2 u}{\partial x^2}+\delta\frac{\partial}{\partial t}\left(\frac{\partial^2 u}{\partial x^2}\right)+F_{ext}(x,t) \quad (1)$$

where ρ is the density, $u(x,t)$ is the particle displacement in the x-direction, $K_2=\rho c^2$ is the bulk modulus where c is the sound velocity, $\beta=-(3K_2+K_3/K_2)$ is the nonlinear parameter and gives a measurement of the material bulk nonlinearity where K_3 is the third-order elastic constant, δ is the damping coefficient and $F_{ext}(x,t)$ is the externally applied force per unit volume.

For the case of a semi-infinite material ($x>0$) where the external force applied at the structure boundary ($x=0$) is sinusoidal, the approximate solution for the nonlinear wave Eq. (1) can be found through use of a perturbation technique [28,26]

$$u(x,t)=\underbrace{\frac{1}{8}\beta\, k_0^2A_1^2x}_{A_0}+A_1\ \sin(-k_0(x-ct))-\underbrace{\frac{1}{8}\beta\, k_0^2A_1^2x}_{A_2}\ \sin(-2k_0(x-ct))+\ldots \quad (2)$$

where $k_0=2\pi f_0/c$ is the wavenumber, f_0 is the frequency of the sinusoidal force, x is the propagation distance, A_0 is the direct current (DC) amplitude, A_1 is the amplitude of the centre frequency output signal and A_n ($n>1$) is the amplitude of the nth harmonic in the frequency spectrum.

In other words, when a sinusoidal wave of amplitude A_{ap} and frequency f_0 (input signal) is sent into a linear medium, the ultrasonic wave measured at a distance x from the structure boundary (output signal) is a sinusoidal wave of amplitude A_1 and frequency f_0. If the medium is nonlinear, then sinusoidal waves of amplitude A_n of frequency nf_0 where $n>1$ called higher harmonics are generated in the output signal. Higher harmonics can be seen in the frequency spectrum of the output signal, and their amplitudes measured.

If the amplitudes of the fundamental and second harmonic can be measured after a certain propagation distance x, then the nonlinear parameter β for the undamped material can be obtained from

$$\beta=\frac{8}{k_0^2x}\frac{A_2}{A_1^2} \quad (3)$$

which involves the calculation of the nonlinear ratio Φ

$$\Phi=\frac{A_2}{A_1^2} \quad (4)$$

The technique that involves the measurement of β and Φ is called the harmonic generation technique.

2.2. Theoretical formulation for a one-dimensional finite-element model

The following FE model is a 1-D discretisation of the continuum into line elements of length Δx, uniform cross-sectional area A and bulk modulus K_2. Each element is subjected to nodal forces resulting in stresses σ and small nodal displacements Δu and strains $\Delta\varepsilon$. Applying the principle of dynamic virtual work, the work done within an element is equal to the external work done by the forces applied at its nodes.

The resulting discretised equation gives the equilibrium equation for each element

$$\{\mathbf{M}\}^e\ddot{\mathbf{u}}+\{\mathbf{D}\}^e\dot{\mathbf{u}}+\left(\{\mathbf{K}_L\}^e+\{\mathbf{K}_{NL}(\mathbf{u})\}^e\right)\mathbf{u}=\mathbf{F} \quad (5)$$

where $\{\mathbf{M}\}^e$, $\{\mathbf{D}\}^e$, $\{\mathbf{K}_L\}^e$ and $\{\mathbf{K}_{NL}\}^e$ are the mass, damping, linear stiffness and nonlinear stiffness element matrices.

These element matrices are then put into place in the global matrix equation by adding each element of the structure

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{D}\dot{\mathbf{u}}+(\mathbf{K}+\mathbf{K}_{NL}(\mathbf{u}))\mathbf{u}=\mathbf{F}_{ext} \quad (6)$$

where $\mathbf{M}$, $\mathbf{D}$, $\mathbf{K}$ and $\mathbf{K}_{NL}(\mathbf{u})$ are the mass, damping, stiffness and nonlinear stiffness matrices respectively, and $\mathbf{u}$ is the displacement vector with its associated derivatives with respect to time ($\ddot{\mathbf{u}}=(\partial^2\mathbf{u}/\partial t^2)$ and $\dot{\mathbf{u}}=(\partial\mathbf{u}/\partial t)$).

The time discretisation of $\ddot{\mathbf{u}}$ and $\dot{\mathbf{u}}$ is accomplished by central and backward difference approximations respectively and Eq. (6) is transformed into the following time-domain computational algorithm

$$\begin{aligned}\mathbf{u}_{t+\Delta t}&=\Delta t^2\mathbf{M}^{-1}\mathbf{F}-\Delta t^2\mathbf{M}^{-1}(\mathbf{K}+\mathbf{K}_{NL}(\mathbf{u}_t))\mathbf{u}_t\\&\quad+\Delta t\mathbf{M}^{-1}\mathbf{D}(\mathbf{u}_{t-\Delta t}-\mathbf{u}_t)+2\mathbf{u}_t-\mathbf{u}_{t-\Delta t}\end{aligned} \quad (7)$$

where Δt is the time step, and $\mathbf{u}_{t+\Delta t}$, $\mathbf{u}_t$, $\mathbf{u}_{t-\Delta t}$ are values of displacements at the three consecutive time instants $t+\Delta t$, t and $t-\Delta t$.

The FE model was implemented in Matlab. The model was validated in the linear regime against experimental data and verified against an analytical model using an input impedance approach analogous to transmission line theory [29]. Validation for nonlinear wave propagation was assumed to be achieved when the specified material nonlinearity parameter β could be recovered from the model output.

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