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Efficient simulations of the nonlinear wave modulation induced by a closed crack using local contact modelling

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Abstract

Nonlinear wave modulation methods have been used for the detection of small defects such as closed cracks or delaminations. These methods rely on the nonlinear interaction of a low frequency pumping wave and a high frequency probing wave, which produces sideband frequencies equal to the sum and difference of the input frequencies. Since two very different frequencies are involved, numerical modelling approaches generally require to run the simulations for a long time in order to achieve a steady state regarding the low frequency excitation. In this work, we propose a numerical model where the low frequency excitation is accounted by a time dependent stress state at the contact interface. This local stress state is the prospective stress in the un-cracked structure due to the pumping wave. This is performed by implementing an additional stress parameter directly in the contact laws used to model the contact dynamics occurring at the crack. The high frequency excitation is generated in the solid by imposing displacements on the boundary of the domain, as done in previous work. This concept is first demonstrated through a 1D Finite Difference model with a contact interface between a semi-infinite solid and a rigid boundary. Secondly, this approach is implemented in a 2D Finite Element model where a closed crack of finite length is considered. The results demonstrate the interest of the method for investigating nonlinear wave modulation, and they provide a benchmark for understanding experimental results that may involve more complicated manifestations of contact acoustic nonlinearity.

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Keywords: NDT; Nonlinear Acoustics; CAN; Modulation; Finite Difference; Finite Element

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1. Introduction

Early damage detection is of considerable interest for effective management of structural integrity. Linear ultrasonic methods have shown considerable success in detecting large defects such as holes or open cracks, but are

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less sensitive to micro-cracks, closed cracks, closed delaminations or barely visible impact damage (BVID). Nonlinear ultrasonics has the potential to detect damage substantially smaller then linear methods, allowing for the prospect of early damage detection [1]. Nonlinear acoustic methods generally rely on the spectral enrichment of the propagating wave due to some form of nonlinear behaviour. In case of closed cracks or delamination, contact acoustic nonlinearity, or CAN [2], is at the origin of the nonlinear behaviour. More precisely, the contact dynamics between the two faces of the defect introduces a strong nonlinear response, which is responsible for the generation of new frequencies.

One of the direct consequences of CAN if the generation of higher harmonics [2], which can be used for detection purposes. However, for small and localized damage, the use of higher harmonics becomes difficult due to their small amplitude and because the contribution of the local defect cannot be separated from the nonlinear contribution of the electronic hardware or the surrounding material. An alternative method is the nonlinear wave modulation technique, which has the ability to detect small levels of localized damage. In a linear system, which corresponds to the non-damaged structure, the principle of wave superposition applies. Considering simultaneous excitations by two distinct frequencies, the net response of the linear system is the sum of the two input frequencies as shown in Figure 1 (a). In a nonlinear system however, the principle of wave superposition no longer applies, and the interaction of waves of different frequencies results in new frequency components as shown in Figure 1 (b). These new frequency components, referred to as sidebands, correspond to the sum and the difference of the HF input and multiple of the LF input. In other words, sidebands appear at discrete frequencies of $f_H \pm nf_L$, where $n = 1,2,3$. Because these sidebands are not generated in the case of the pristine structure, nonlinear wave modulation can be used for detection purpose [3]–[6].

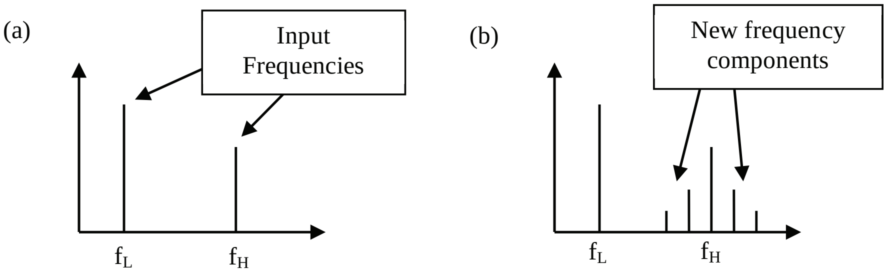

Figure 1: a) Linear system response showing only the two excitation frequencies and b) nonlinear system response showing the generation of new frequency components due to frequency mixing.

Numerically, several models have also been studied for the analysis of CAN, based on different computational approaches, such as nonlinear spring models [7], Preisach-Mayergoyz space representation [8], or contact laws [9]–[13] involving unilateral contact and/or Coulomb friction. As regard nonlinear wave modulation, numerical modelling generally requires running time-explicit simulations for a long time in order to achieve a steady state regarding the low frequency excitation [14], [15]. The CAN is then either accounted by spring models [14], or contact laws [6], [15]. Moreover, reducing the computation domain by using absorbing layer such as Perfectly Matched Layer (PML) is not pertinent, because PML dimensions need to equal the longest wavelength at stake. For these reasons, nonlinear wave modulation modelling generally results in high computing cost.

This work proposes a numerical modelling of the nonlinear wave modulation in which the low frequency excitation is not explicitly imposed at the simulated domain boundary, but rather incorporated in the contact laws used to account for CAN as a time dependent stress condition. With this approach, only the high frequency wave is generated in the solid and PML can be used to reduce the computation domain. Moreover, steady state of the low frequency excitation is directly achieved, which further reduce the computation time. This approach is first demonstrated with a simple 1D Finite Difference (FD) model and then extended to a 2D Finite Element (FE) model.

2. Numerical models

In this work, the nonlinear wave modulation is assumed to be due to CAN occurring at a defect such as a closed crack. The defect is modelled as a contact interface where CAN is modelled here using contact laws that account for