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Critical aspects of experimental damage detection methodologies using nonlinear vibro-ultrasonics

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Abstract

Nonlinear ultrasonics has become a major research focus in non-destructive testing (NDT) in recent years. Techniques using higher harmonics or cross-modulation of two excitation frequencies have been developed and have shown to be extremely sensitive and to allow measuring defects that are undetectable using conventional ultrasonic NDT. This paper reports on the application of nonlinear vibro-ultrasonics to detect delamination damage in composite laminate beams. In addition, measurement and data analysis requirements are evaluated to ensure optimal sensitivity, reliability and robustness of nonlinear vibro-ultrasonic damage detection systems. The importance of the individual components of the measurement chain is demonstrated, and a measurement system is described that has a dynamic range of more than 120 dB and 24-bit amplitude resolution, which enables the measurement of sideband frequencies with unprecedented sensitivity and accuracy. The influence of the selection of input variables such as excitation frequencies and input voltages on the sensitivity of the system is also demonstrated. It highlights the challenges of reliable damage evaluation in the case of materials and structures with unknown damages. The conclusion of the paper is that nonlinear vibro-ultrasonics has great potential as NDT technique with unmatched sensitivity, but that measurement systems and experimental parameters and processes have to be selected and optimised with extreme care to ensure that damage detection results are reliable.

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1. Introduction

Today's high performance engineering applications push materials and structures closer to their design limits in all fields of engineering. Hence, it has become increasingly important to develop more sensitive tools and techniques for the early detection of defects to ensure the safety and reliability of critical infrastructure. Of all techniques typically

used for non-destructive testing (NDT) ultrasonic NDT is clearly the most prolific. With the ability to detect cracks and defects, to identify impact damage, to analyse weld integrity and to measure thicknesses of critical components ultrasonic NDT finds widespread use in almost every engineering discipline. But conventional linear ultrasonic NDT has its limitations. For example materials and structures with closed cracks or near surface delaminations as well as adhesively bonded structures are difficult to inspect.

These limitations were the motivation to investigate nonlinear ultrasonic techniques using higher harmonics or cross-modulations which exploit nonlinear interactions that occur as elastic waves travel through damage areas [1-7]. These techniques are often cited to be more sensitive to low levels of damage and have thus gained considerable prominence in applications where early detection of low levels of damage is essential.

One particularly promising technique involves exciting a structure simultaneously with a probing ultrasonic wave and a second, lower-frequency pumping wave. Depending on the nature of pumping excitation, the technique has been referred to by authors as vibro-acoustic modulation [1,4], nonlinear ultrasonic modulation [5], and nonlinear wave modulation spectroscopy [6,7]. In this paper, we refer to the technique as *nonlinear vibro-ultrasonics*, in order to emphasize that it is a nonlinear ultrasonic technique which utilises vibration excitation as a pumping wave to interact with the probing carrier wave.

Linear elastic wave theory predicts that two excitations simply superimpose, and that the structure's response spectrum is made up only of the two input frequencies, as shown in Figure 1a. Nonlinear vibro-ultrasonics relies on the fact that this is not the case, due to nonlinearity inherent in the structure or that caused by a defect. Instead, when the probing and pumping waves interact in the presence of nonlinearity, frequency mixing of the waves occurs. This nonlinear frequency mixing generates additional waves at sideband and harmonic frequencies. An illustration of this where the probing wave is amplitude modulated by the pumping wave is shown in Figure 1b. In the example shown, two sidebands are present at the sum and difference frequencies of the probing and pumping waves. The number and characteristics of these additional frequency components is dependent on the type of nonlinearity encountered.

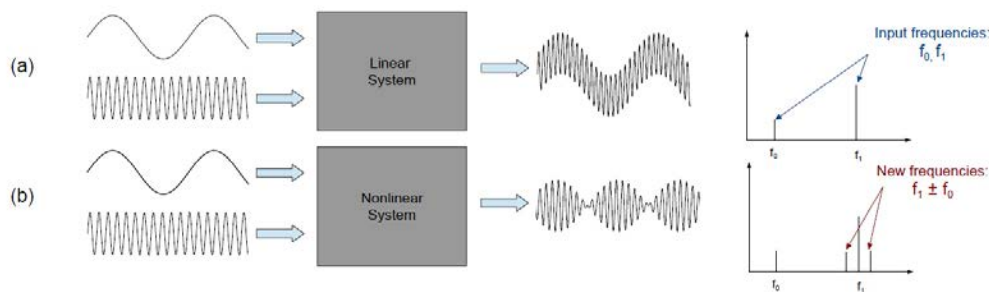


Figure 1: The response of (a) linear and (b) nonlinear systems to two excitations

The technique was first described in literature for its applications in detecting cracks in steel bars, using either an impact hammer or vibration shaker as the low frequency pumping excitation. In recent years the technique has been extended to the detection of cracks in glass and aluminium [1,5], and delaminations and impact damage in composite laminates [3,4,7].

An example response spectrum from nonlinear vibro-ultrasonic experiments is shown in Figure 2. This data was collected using the experimental apparatus described below. A composite laminate beam sample was excited by a probing frequency of 380 kHz and a vibration pumping frequency of 60 Hz. In the response six pairs of sidebands are visible at multiples of 60 Hz either side of the 380 kHz carrier. Subsequent sidebands are not visible because their spectral amplitude is below that of the noise floor which is approximately between -135 dB and -125 dB in the relevant frequency range. Circumstances leading to lower spectral amplitude (e.g. lower amplitude or higher attenuation of excitations, smaller cross-modulation) or a higher noise floor (e.g. interference, measurement equipment, signal processing) would lead to less visible sidebands. This means that the sensitivity of nonlinear ultrasonic methods is tied to the ability of the measurement system to resolve individual sidebands and experimental methods which rely on the measurement of these spectral amplitudes have to be carefully designed to maximise the amplitude of these sidebands relative to the noise floor.

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