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Nonlinear non-collinear ultrasonic detection and characterisation of kissing bonds

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ABSTRACT

The development of cost effective and reliable bonded structures ideally requires an NDT method to detect the presence of poor quality, weak bonds or kissing bonds. If these bonds are more compliant in tension than in compression stress-strain nonlinearities provide a possible route to detection with the use of nonlinear ultrasonic techniques. This paper focuses on the kissing bond case and the resulting contact acoustic nonlinearity of the interface. A kissing bond is created by compression loading of two aluminium blocks. Non-collinear mixing of two shear waves producing a sum frequency longitudinal wave is the method of stimulation of contact acoustic nonlinearity in this research. The parametric space of the nonlinear mixing is measured in terms of interaction angle of the input beams and the ratio of their frequencies creating a ‘fingerprint’ of the sample's bulk and interface properties in the region where the beams overlap. The scattering fingerprint of a classically nonlinear solid is modelled analytically and a kissing interface is modelled numerically; these results are compared with experimentally measured values. The experimental interface is tested with varied interfacial loading, resulting in an increase in scattering amplitude as load is increased. Secondary peaks in the parameter space also appeared as loading increased, as well as other changes in the fingerprint pattern.

1. Introduction

Kissing bonds, two surfaces in intimate contact but not bonded together, can be difficult to detect with the non-destructive testing (NDT) techniques that are standard in industry today [1,2]. For this reason, some structures are over-engineered to allow for the safe failure of an adhesive joint; ‘chicken rivets’ in aeronautical structures are an example of this. Kissing bonds are hard to detect with conventional ultrasound techniques because the kissing interface has a transmission coefficient very similar to the properly bonded case. This is particularly true when the interface is under compressive load. If enough acoustic stress can be applied to the interface the kissing bond will open during the tensile part of the wave. This opening and closing of the interface causes contact acoustic nonlinearity (CAN), clipping parts of the waveforms and transferring energy into other harmonics [3,4]. The research presented here aims to investigate this CAN behaviour in order to create a method for reliable, spatially sensitive, detection of kissing bonds.

There are many possible ways to detect the acoustic nonlinearity of a kissing bond. Measuring the change in transmission/reflection of the fundamental frequency is the simplest but it is insensitive due to the small changes involved [4,5]. Detecting the harmonics produced is more sensitive [1] but the harmonics often have other potential sources such as the amplifiers, transducers, couplant or the bulk materials themselves [6,7]. To overcome these problems a more advanced technique is required such as non-collinear mixing, pioneered by Jones and Kobett, and Rollins [8–10] in the 1960s. In non-collinear mixing two beams follow different paths that overlap in an area of interest. In this overlap region nonlinearities can cause the two waves to interact with each other producing a new one. The scattered beam travels in a different direction from the input beams separating its signal from the system harmonics present in the input beams that might otherwise obscure it. This creates a method which is spatially selective and when combined with filtration techniques makes it highly sensitive.

One of the conditions that must be met for bulk nonlinear mixing to occur is that the geometry of the input beams' interference pattern is such that the spacing of the antinodes is the same as the wavelength corresponding to the sum or difference of the input frequencies. The two key parameters that control the geometry of the interference pattern are the angle at which the two beams overlap (referred to as

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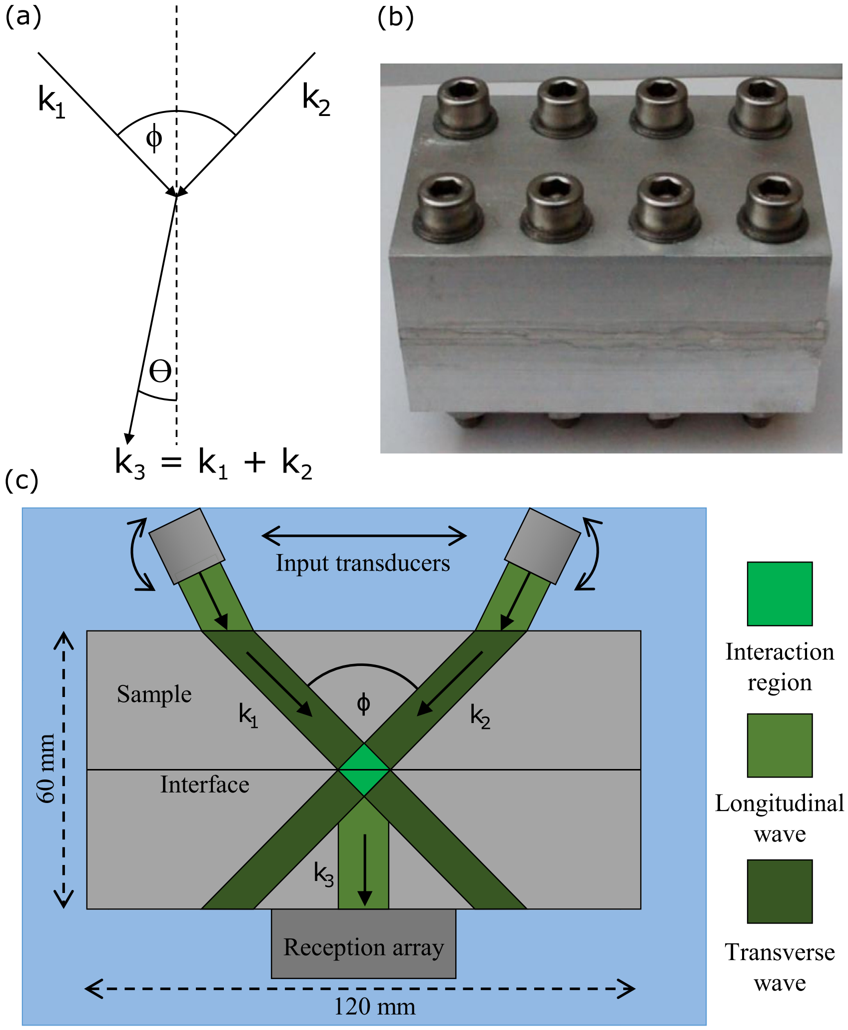

Fig. 1. (a) General interaction geometry of non-collinear mixing, ϕ is the interaction angle and θ is the scattering angle. (b) Photograph of bolted aluminium sample used to simulate a kissing bond. There is sealant around the loaded interface to prevent the ingress of water. (c) Scale diagram of the experimental layout, showing simplified ultrasonic beam paths and wave types. The test is conducted in immersion.

interaction angle) and the ratio of their frequencies. The optimal conditions were defined as ‘resonant conditions’ in Ref. [8].

Within the volume of interaction there are two main sources of nonlinearity; the classical nonlinearity of the solids [11], corresponding to the intrinsic bulk nonlinearity, which allows for the mixing of the two input beams as described by Refs. [8,9], and the CAN. CAN generates a signal from the kissing bond in the non-collinear case by the combined acoustic forces of the two input waves opening, closing, or unloading the interface enough to allow them to slip when it would be in a different state if only a single wave were applied. This modulation generates harmonics in a similar way to the single beam case. These perturbations effectively create an array of acoustic sources on the interface which together produce plane waves. Another difference between bulk and CAN mixing is that the latter produces scattered beams in both directions from the interface [12,13]. This can be thought of as being caused by the reflection from the interface when the two overlapping waves open it when it would be closed in the single beam case. This effect was not exploited in the following research due to difficulties in positioning an array between the input transducers but the results from transmission testing should be informative of likely reflective behaviour which would be useful for developing a one-sided NDT inspection tool.

Non-collinear mixing has been used to investigate the state of many different materials including; physical ageing of thermoplastics [14], epoxy curing [14], fatigue in aluminium [15], and oxidative aging of asphalt [16]. Research into the behaviour of kissing bonds with non-collinear ultrasonic mixing is limited. Demčenko et al. conducted testing on PVC plates [17], and there has been modelling conducted by Blanloeuil et al. [13], and Zhang et al. [18]. The modelling by Zhang et al. focuses on an infinite interface with nonlinear stiffness terms in one case, and a thin region of hyperelastic solid in another case. These differ from the work presented here as their interfaces never open but the results are similar in many ways. In Demčenko's work the interaction between shear and longitudinal beams overlapping at a kissing bond at fixed angles is investigated. If the interface is defined as the x-z plane then the input beams were tested with interaction planes of x-z and y-z. When operating in the y-z plane the beams approached the interface from opposite sides. The study showed that the interface led to a reduction in nonlinear wave signal in both interaction planes. In the work presented here the input beams are in the y-z plane but both approach the interface from the same side.

Current methods consider the response for single values of interaction angle, ϕ, and frequency ratio, a, usually selected to satisfy the resonance criteria. The scattered wave amplitude however may be evaluated for a range of these parameter values, producing a surface within the a-ϕ parameter space. There is more information about the material contained within the full parameter space than can be recovered from a single experimental operating point. For classical

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