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Closed crack imaging using time reversal method based on fundamental and second harmonic scattering

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ABSTRACT

A recent variant of time reversal imaging is employed for reconstructing images of a closed crack, based on both the fundamental and the second harmonic components of the longitudinal scattered field due to an incident longitudinal wave. The scattered field data are generated by a finite element model that includes unilateral contact with Coulomb friction between the crack faces to account for the Contact Acoustic Nonlinearity. The closure state of the crack is controlled by specifying a pre-stress between the crack faces. The knowledge of the scattered field at the fundamental (incident) frequency and the second harmonic frequency for multiple incident angles provides the required inputs for the imaging algorithm. It is shown that the image reconstructed from the fundamental harmonic closely matches the image that is obtained from scattering data in the absence of contact, although contact between the crack faces reduces the amplitude of the scattered field in the former case. The fundamental harmonic image is shown to provide very accurate estimates of crack length for low to moderate levels of pre-stress. The second harmonic image is also shown to provide acceptable estimates of crack length and the image is shown to correlate with the source location of second harmonic along the crack, which becomes increasingly localized near the crack tips for decreasing levels of pre-stress. The influence of the number of sensors on the image quality is also discussed in order to identify the minimum sensors number requirement. Finally, multiple frequency imaging is performed over a fixed bandwidth to assess the potential improvement of the imaging algorithm when considering broadband information.

1. Introduction

Early detection and characterization of structural damage is of prime interest for effective structural integrity management. Nonlinear ultrasonics has attracted considerable attention recently because it offers the possibility of detecting various forms of material and structural damage earlier than can be achieved by conventional linear ultrasonics. The present work is concerned with cases where the source of nonlinearity can be attributed to localized contact within planar defects such as cracks and delaminations, which is referred to as contact acoustic nonlinearity (CAN) [1–5], as distinct from cases where the nonlinearity is distributed throughout the bulk of the material, due, for example, to distributed fatigue damage [6–9]. The focus of current research has evolved from simply aiming to detect the presence of CAN to the

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more ambitious aim of imaging the damage, *i.e.* being able to locate and size the damage, and, ultimately, of assessing the severity and the structural significance of the damage. This paper combines a recent comparative evaluation of imaging algorithms [10,11] with a high-fidelity computational model of CAN [12–14], with the objective of assessing the image quality that can be achieved when using as input data either the fundamental or the second harmonic component of the scattered field due to a toneburst excitation. The resulting images can be expected to provide a benchmark for what could be achieved in practice, where it is not always possible to satisfy the imaging requirements of a full-view configuration, or of adequate sampling of the scattered field, and where the input data is inevitably contaminated by measurement noise.

Three imaging algorithms were rigorously evaluated and compared in [10], viz. (i) generalized diffraction tomography [15–17], also known as linearized inverse scattering [18]; (ii) beamforming [19–21], also known as delay-and-sum [22], synthetic aperture focusing technique (SAFT) [23,24], total focusing method [25–27]; and (iii) reverse time migration [28–30] or time reversed imaging [31–33]. It was noted in [10] that only (i) has a rigorous mathematical basis, whereas (ii) and (iii), though widely used in practice, are based on heuristic arguments. A modified form of reverse time migration was formulated in [10] and recommended for practical application because it combines the ease of implementation of (ii) and (iii) with the correct point-spread-function of (i). This modified time reversal (MTR) algorithm was further investigated in [11,34,35], and it will be used in the present work.

Previous attempts at nonlinear ultrasonic imaging can be divided into two groups depending on whether the image reconstruction process involves (i) a point by point scanning of the ultrasonic response at every point (or pixel) within a prescribed imaging domain, usually (but not necessarily) using a laser vibrometer [36–47], or (ii) implementing an imaging algorithm that uses as input the measurements recorded by a sensor array deployed around and outside the imaging domain [48–65]. The present work belongs to the second group, which is of greater interest for structural health monitoring based on built-in sensor arrays. Nevertheless, it is pertinent to comment briefly on some aspects of the work in the first group, to further clarify the difference with the present work. In [37–42], time reversal is used as an experimental technique to achieve array focusing at a given point, the response at that point being then measured directly and processed to extract the value of the image at that point. The premise in this approach is that the chosen measure of nonlinearity that is being used to construct the image will attain a maximum value at the location of the source of nonlinearity. However, the computational results presented in [40] indicate that this premise is not verified, because the maximum is found at 3 mm away from a crack, which is the only source of CAN in the model. This highlights the value of simulations in guiding the design and interpretation of experiments. It is also noted that the MTR algorithm entails a synthetic focusing (based on time reversal), rather than the operation of a time reversal mirror to achieve a physical focusing, as used in [39,40] and related work.

Several strategies have been proposed for nonlinear ultrasonic imaging within the second group, *i.e.* where the image is constructed via an algorithm utilizing remotely acquired data. Kazakov et al. [53] and Jiao et al. [54] employed conventional imaging techniques (B-scan and beamforming, respectively), but with a superimposed low-frequency vibration. The imaging strategy is that the response from linear scatterers is not affected by the vibration, whereas the response from nonlinear scatterers depends on the instantaneous stress level during the vibration cycle, so that by subtracting images obtained at the peak and at the trough of the vibration cycle, one is left with an image of only the nonlinear scatterers, because the image of linear scatterers would cancel out during the subtraction. A related strategy is proposed by Potter et al. [56] who note that the response of a nonlinear scatterer to a parallel (*i.e.* simultaneous) transmission from a phased array, with appropriate time delays to focus on a chosen location, is different from the sum of the responses using sequential transmission, because the nonlinear response does not vary linearly with the amplitude of the input excitation. However, their approach for exploiting this difference involves choosing a suitable delay time that represents a compromise between maximizing the response amplitude and establishing diffuse field conditions due to multiple boundary reflections. This choice would appear to require a trial-and-error approach. Ohara et al. [57–59] have proposed phased-array imaging of the subharmonic response generated by partially closed cracks in fatigue-cracked specimens when the input amplitude exceeds a threshold of around 50 nm, and they demonstrated an enhanced selectivity by subtracting images obtained at different values of applied load. In a recent extension of that approach, the MUSIC (Multiple Signal Classification) algorithm was used to obtain sharper images [60]. The strategy pursued in the present work is most closely related to that originally proposed in [61,62], which is to use a higher harmonic component of the scattered field as the input to an imaging algorithm based on time reversal. However, [61] does not provide an explicit imaging condition, whereas [62] employs the DORT (French acronym for Decomposition of the Time Reversal Operator) algorithm which is appropriate for well-resolved point-like scatterers, *i.e.* scatterers that are individually small compared with the wavelength, and spaced sufficiently far apart for multiple scattering contributions to be negligible; (see [66] for a brief review). By contrast, the MTR algorithm is suitable for extended scatterers, albeit subject to the applicability of the distorted-wave Born approximation [16].

Theoretical analyses of CAN have often been based on simplified models for the contact dynamics that have nevertheless provided valuable insights for designing and interpreting experimental studies [1–5]. However, several more detailed models have also been studied, based on different computational approaches, viz. (i) hypersingular integral equations [67,68]; (ii) time-domain finite difference [69,70]; and (iii) finite-element (FE) method [12,14,40,71]. The present work uses the open source FE package Plast2 [72,73] as already used in [12,14], which has the particularity to make use of the Lagrange multipliers method to solve the contact problem in a robust way.

As noted earlier, the objective of this work is to document the imaging performance that can be achieved by using either the fundamental or the second harmonic component of the scattered field as input to the MTR imaging algorithm. The presentation is organized as follows. Section 2 describes the imaging configuration and Section 3 the imaging algorithm. The