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Identification of breathing type disbonds in stiffened panels using non-linear lamb waves and built-in circular PWT array

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A non-linear Lamb wave based active sensing technique for identification of breathing type disbonds in stiffened metallic plates has been presented. In this technique, a built-in dual transmitter and multi receivers (DTMR) clock-like array of piezoelectric wafer transducers (PWT) is used. The central part of the array consists of two transmitters, which are placed concentrically on either side of the plate. A Hanning window modulated sine pulse has been used for excitation. Opposite polling is applied to the transmitters to generate a predominant anti-symmetric (A_0) Lamb mode to encourage breathing in the disbond. It is observed that the contact acoustic nonlinearity (CAN) of breathing disbond generates higher harmonics when a primary Lamb wave interacts with the disbond. Since these harmonics carry damage information, a bandpass filter is used to extract the second harmonic component from the received signals followed by wavelet transformation. Finally, the transformed signals are used to device a baseline free damage detection algorithm for locating the disbond. Experimental investigations are carried out to interrogate a full width disbond that is located either at the middle of the T-stiffener or at an offset from its center. The damage index (DI) map obtained for the entire plate show higher values at the disbond location. Once the disbond is localized, a damage quantity (DQ) curve is devised to determine the extent of disbond with a high degree of accuracy. Extensive numerical simulations are carried out using commercially available finite element package, ANSYS 14.0, in an effort to examine the effectiveness of the damage detection algorithm and to further establish the DQ curves. The numerical results are found to be in good agreement with the experimental findings that affirm the robustness of the nonlinear active sensing technique for detection and assessment of breathing type disbond in stiffened aluminium panels without requiring the baseline signals.

1. Introduction

The initiation of a disbond is very common in laminated composite structures or in between metallic surfaces joined together by means of adhesives or weld. Although, at an early stage it seems to pose no threat to the structure, but its rapid growth incurs a significant reduction in strength, while showing no visible outside symptoms. As an example, welded joints of a steel structure are highly susceptible to initiation of disbonds because of high residual stress, stress concentrations and

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faulty welding. Hence, the development of an efficient algorithm which ensures early detection of damage, thereby enforcing increased safety, durability and improved economic operation of a structure, is of paramount importance.

The interests in structural health monitoring (SHM) using ultrasonic wave propagation are growing continuously, since the wave propagation characteristics are linked to the material properties, as well as, geometric conditions (e.g., presence of internal discontinuity) of these structures. The traditional ultrasonic non-destructive techniques are based on linear theory in which usually velocity, attenuation, reflection and transmission of the waves are measured to determine the material properties or the presence of defects in a structure [1]. In a linear theory based technique, usually the phase and/or amplitude of the probing signal is changed but the frequency content remains unchanged in the presence of defects [2]. The existing ultrasonic methods include, the pulse-echo, the pitch-catch and through transmission [3]. In the pulse-echo, defects are detected by the additional echoes captured in a receiver, while, in pitch-catch, wave dispersion and attenuation are used as flaw indicators [4]. In the thickness-wise inspection the wave path traverses only a small portion of the structure, hence, the transducer is mechanically moved along the surface to scan, as well as, to interrogate the entire structure [5].

Although, the conventional ultrasonic methods are sensitive to gross defects or open type damage (e.g., narrow slit, circular hole) [5], but not sensitive to micro fatigue cracks in various materials [6] or contact type non-linear damage (e.g., disbonds, breathing cracks) in metallic and composite structures [7].

In recent years, the nonlinear acoustic phenomena have attracted attention of many researchers since these are linked to various imperfections in the atomic lattice (i.e., intrinsic or material nonlinearity) [8] and also to the interface nonlinearity (e.g., breathing cracks, contacts, rubbing surfaces) [8]. Some important features related to nonlinear effects in solids have been investigated include: time-domain signal distortion, generation of higher harmonics, resonance frequency shift, signal modulation, slow dynamics, and nonlinear dissipation [2,9]. Although, there are many specialized techniques developed in nonlinear acoustics, those which attracted more attention are: higher harmonic generation [8], nonlinear resonate ultrasound spectroscopy (NRUS) [9], and nonlinear elastic wave spectroscopy (NEWS) [10]. Especially, the generation of a new frequency component while nonlinear wave-damage interaction is very interesting and sensitive [2,9], which not only makes the nonlinear acoustic much different from the conventional ultrasonic, but also, gives an edge the former over the later in the detection and characterization of nonlinear defects. Hence, many researchers are trying to adopt the nonlinear acoustic to overcome the limitations of the conventional ultrasonic methods mentioned before.

The earlier account on characterization of material microstructure (i.e., material nonlinearity) and dislocation nonlinearity using higher harmonics produced by the bulk waves excitation have been mentioned [9]. Many researchers [6,11] have used nonlinear acoustics for fatigue damage assessment in different materials (e.g., Aluminum-based alloy, Titanium-based alloy). They found that there is a considerable increase in the nonlinearity parameters (e.g., acoustic nonlinearity parameter, β) with the increase in fatigue cycle, while linear parameters (e.g., velocity) remain almost the same.

Although, an ample amount of work has been done over the course of last few decades in nonlinear acoustic regime using bulk and surface waves [2], the research associated with the nonlinear guided Lamb waves is sparse. The dispersion (i.e., frequency dependent wave velocity, which also implies that, the secondary/nonlinear Lamb waves produced in a nonlinear interaction, owing to its different frequency content than the primary/fundamental Lamb wave, may travel at different velocities than the fundamental portion [12]) and the multimodal propagation characteristics [13] inherent to guided waves not only make them different from the bulk and surface waves (having none of those characteristics), but also, make the former associated with more complex analysis, and, the complexity increases further when nonlinearity is involved. In determining the location and the degree of defects in thin plate-like structures [14,15] linear guided waves provide following advantages [4,16]: (1) easy to generate and receive using piezoelectric transducers; (2) propagate a long distance; (3) inspect a large area and entire cross-section without the need of expensive motion devices; (4) can detect different types of damage by utilizing multi modal characteristics in metallic [17,18] or composite [19,20] structures. Therefore, the interest in nonlinear guided waves has grown naturally with a view to characterize incipient damage in those structures by exploiting these advantages with added benefits (i.e., high sensitivity and ability to detect incipient damage [6]) of the nonlinear acoustics.

An early investigation of the second harmonic generation in solid plates has been carried out by Deng [21], where an analytical expression has been determined for the cumulative Lamb-mode propagation using partial-wave technique [22]. Only the resonate second-harmonic wave (whose phase velocity matches with the primary/fundamental one) has been considered in the analysis. Lima and Hamilton [23] used perturbation to obtained the solution for higher harmonics considering all modes (i.e., both resonate and non-resonate) of the secondary wave field in a stress-free elastic waveguide. It was described that the two conditions which are essential for internal resonance to occur that result in cumulative growth of harmonic in the direction of propagation are: phase velocity matching of the primary with the secondary wave, and nonzero power transfer from the primary to the secondary wave [21,23]. Since, in reality usually a short duration pulse consisting of a narrow band frequency content is used as the diagnostic signal which propagates with a particular group velocity, according to Lee et al. [24] an additional condition (i.e., group velocity matching) is necessary for the generation of cumulative nonlinear guided wave. Deng and Pei [25] have used the second harmonic of the primary Lamb wave in the assessment of fatigue damage, which has been accumulated in the specimen (i.e., aluminium sheets) due to the application of tension–tension fatigue loading. A parameter, termed as, stress wave factor [26], has been calculated for different fatigue cycles and the parameter was found to be highly sensitive to the fatigue cycle [25]. Yang et al. [27] investigated the scattering feature of the second harmonic in fatigued aluminium plates and it was found that the magnitude of the second harmonic Lamb wave is higher in the forward and backward scattering directions. Thermal fatigue damage assessment in composite laminates has been carried out using second harmonic of the probing Lamb waves [28]. The correlation between acoustic nonlinearity and