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Locating fatigue damage using temporal signal features of nonlinear Lamb waves

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A B S T R A C T

The temporal signal features of linear guided waves, as typified by the time-of-flight (ToF), have been exploited intensively for identifying damage, with proven effectiveness in locating gross damage in particular. Upon re-visiting the conventional, ToF-based detection philosophy, the present study extends the use of temporal signal processing to the realm of nonlinear Lamb waves, so as to reap the high sensitivity of nonlinear Lamb waves to small-scale damage (*e.g.*, fatigue cracks), and the efficacy of temporal signal processing in locating damage. Nonlinear wave features (*i.e.*, higher-order harmonics) are extracted using networked, miniaturized piezoelectric wafers, and reverted to the time domain for damage localization. The proposed approach circumvents the deficiencies of using Lamb wave features for evaluating undersized damage, which are either undiscernible in time-series analysis or lacking in temporal information in spectral analysis. A probabilistic imaging algorithm is introduced to supplement the approach, facilitating the presentation of identification results in an intuitive manner. Through numerical simulation and then experimental validation, two damage indices (DIs) are comparatively constructed, based, respectively, on linear and nonlinear temporal features of Lamb waves, and used to locate fatigue damage near a rivet hole of an aluminum plate. Results corroborate the feasibility and effectiveness of using temporal signal features of nonlinear Lamb waves to locate small-scale fatigue damage, with enhanced accuracy compared with linear ToF-based detection. Taking a step further, a synthesized detection strategy is formulated by amalgamating the two DIs, targeting continuous and adaptive monitoring of damage from its onset to macroscopic formation.

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1. Introduction

Lamb waves, the elastic disturbance disseminating in a thin plate or shell-like structure, have been the subject of intense scrutiny over the years, based on which a diversity of nondestructive evaluation (NDE) and structural health monitoring (SHM) techniques have been deployed, in a cardinal effort to warrant the reliability, integrity and durability of aging engineering structures. Central to an increasing awareness of the use of Lamb waves is their appealing merits including the ability of promptly interrogating a large area with only a few transducers, the capacity to omni-directionally access hidden components, the high sensitivity to various types of damage, as well as the prospect for implementing in-situ SHM. The majority of present Lamb-wave-based NDE and SHM techniques exploit changes in the temporal signal features in the time domain, with respect to baseline signals, in the form of deviations in wave amplitude and/or phase. Of particular interests among the temporal signal features are time-of-flight (ToF) [1–3], wave reflections/transmissions [4,5], energy dissipation [6], and mode conversions [7], to name a few.

In this backdrop, the theory and interpretation of temporal features of Lamb wave signals are prevalently based on the linear elasticity—extracting signal features at the frequency band at which the probing signals are generated. In that sense, the temporal features, for example the delay in ToF, show, to some extent, linear correlation with the alteration of material or structural parameters due to the damage. Thus, they are referred to as *linear temporal features* of Lamb waves in what follows, and the associated signal processing exercises as *temporal features processing*. In particular, the ToF, one of the most straightforward yet informative linear temporal features, has proven effectiveness in locating gross damage (*viz*., the damage with a characteristic dimension comparable to the wavelength of the probing waves) such as open cracks, through-holes, and voids [8,9].

Yet, insofar as observed, the sensitivity of linear temporal features of Lamb waves is substantially restricted and wavelength-dependent. When used to characterize undersized damage, such as barely visible fatigue cracks or material degradation prior to the formation of discernable, macroscopic damage, these linear temporal features may become less sensitive. This is because inconspicuous damage (much smaller than the probing wavelength) would hardly alter linear temporal features and incur notable wave scattering phenomena. As a remedial measure, one can increase the excitation frequency of probing waves to achieve a reduced wavelength, but this is at the expense of introducing additional complexity to the signal appearance owing to the multimodal and dispersive properties of waves at higher frequencies. Therefore, when dealing with small-scale damage, linear temporal features of Lamb waves may compromise their effectiveness and accuracy.

As opposed to using linear temporal features, continued efforts have been casted to explore the nonlinear features of Lamb waves, with a hope to enhance the detectability of small-scale damage or even material degradation. When the probing Lamb waves traverse an elastic medium, the inherent nonlinearities of the medium and additional nonlinearities arising from possible damage can distort the probing waves. This results in a range of nonlinear attributes in the acquired Lamb wave signals, as evidenced at twice, thrice or higher-fold the probing frequency (a.k.a. fundamental frequency)—termed higher-order harmonics [10–14]; or at half of the probing frequency—comparatively called sub-harmonics [15]; or at mixed frequencies when another excitation (rather than the fundamental frequency) is used to modulate the probing waves (*e.g*., spectral sidebands in nonlinear wave modulation spectroscopy) [16–19], *etc*. These nonlinear attributes can be locally intensified when the probing Lamb waves pass through the damaged region where the damage-induced nonlinearities exist. For example, according to the "breathing crack model" under cyclic loads [20], when a crack closes, compressive and shear stresses of propagating waves are transmitted through the crack; when the crack opens during dilation, waves are partially decoupled. These will jointly lead to a local nonlinearity widely recognized as the *contact acoustic nonlinearity* (CAN). The higher-order harmonics generated therein, especially the second-order harmonic (as the third- and higher-order harmonics are usually too weak in magnitude to be perceptible in the signals), have gained prominence in characterizing undersized fatigue damage [11–14]. As fatigue damage introduces such local nonlinearities in the material when interacting with probing waves, the magnitude of the second-order harmonics in a captured Lamb wave signal can accordingly serve as an indicator to the presence of fatigue damage in the monitored structure. In addition, as the mechanism of this kind of detection is based on nonlinear features of Lamb waves in the frequency domain, its effectiveness is, in principle, less restricted by the probing wavelength than using linear techniques. Input waves in a moderate frequency range can entertain the demand of the evaluation of small-scale damage.

However, to put it into perspective, identification, extraction, and interpretation of nonlinear features of Lamb waves in these approaches are usually implemented *via* a spectral analysis in the frequency domain, at the expense of losing temporal signal features such as the ToF. Consequently, this creates an obvious barrier to reaching quantitative damage localization. Among a limited number of exceptions, Kim et al. [21] explored the spatial variation of the normalized acoustic nonlinearity parameter of longitudinal waves acquired from various propagation paths with different distances to a fatigue fracture site. Such a correlation was then extended to Lamb waves later [22], accounting for a variety of wave propagation lengths and angles of incidence. Nevertheless, because this nonlinearity parameter would decrease rapidly to an uninformative level as the sensing path moves away from the damage site, this approach entails a dense sensor network configuration with sensors deliberately and strategically positioned. Thus, it diverged from the paradigm of SHM which preferably uses sparse sensor networks with minimum intrusion to the host structure. On the other hand, in order to perceive weak nonlinear features of Lamb waves, handheld bulky wedge ultrasonic transducers are usually used, to be manipulated in a narrow frequency band with a concentrated intensity. All of these have posed another challenge towards practical realization of in-situ SHM. Last but not least, nonlinear features of Lamb waves can be much more prone to environmental and instrumentation noise than