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Enhanced damage imaging of a metallic plate using matching pursuit algorithm with multiple wavepaths

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A B S T R A C T

Waveforms received by sensors resulting from multiple wavepaths overlap and are hard to interpret. Because of this difficulty, they are usually intentionally ignored, thereby only the first arrival of wave mode being used for damage localization. This article proposes an imaging algorithm for damage localization by incorporating multiple wavepaths using piezoelectric wafers affixed on a metallic plate. Matching pursuit (MP) algorithm to enhance image quality is adopted for separating each wave packet individually. MP algorithm is an adaptive time-frequency signal decomposition technique that matches the best-fit elementary atom functions from an overcomplete dictionary. This study proposes a new dictionary composed of atom functions that constitute possible wave packets propagated by an excitation of Hann-windowed toneburst. The proposed dictionary converges faster and separates individual wave packets more accurately than typical Gaussian based dictionaries. Simulated studies first confirm the performance of MP algorithm with the proposed dictionary in comparison with those using conventional non-adaptive time-frequency analysis as well as MP with heuristic Gaussian-based dictionaries. The results of this study validate the proposed algorithm that multiple wavepaths can localize the damage with three to four piezoelectric wafers versus typical approaches employing only primary scattered waves.

1. Introduction

In the last decades, a wealth of research on in-situ structural health monitoring (SHM) techniques has been conducted to enhance safety and reliability and to prolong the lifespan of civil, mechanical, and aerospace structures. SHM basically considers inspection in real time and in operation, which differs from conventional non-destructive evaluation (NDE) in that it requires off-line inspection to detect the presence of damage. Furthermore, SHM utilizes global inspection technique with autonomous system; in contrast, NDE uses local inspection through a skilled technician which is time consuming, high cost, and inherently subject to human error.

The use of ultrasonic guided waves for damage detection [1,2] has shown great potential due to the feature that inspects large structural area and their sensitivity to small defects in the structure. In particular, the ultrasonic guided waves in metallic plate-like structures are called Lamb wave, which travels over long distances along the plate surface as well as through the thickness of the structure with little attenuation. Sparsely distributed piezoelectric wafers permanently bonded on a plate surface are one of the most common configuration to interrogate the structure by propagating the Lamb wave, which basically utilizes the electromechanical coupling between the piezo wafers and the structure [3]; a piezoelectric wafer is activated with a dynamic voltage to interrogate the plate with a specific waveform, and the information on the resulting scattered wave field is collected from other wafers (Fig. 1).

For the sparse array of piezoelectric wafers, damage imaging technique is an attractive tool to provide an intuitive visualization that effectively localizes damages in a structure. Damage imaging algorithms based on time-of-arrival (TOA) is probably the most well-known damage localization techniques utilizing the sparse array of piezoelectric wafers. TOA is a straightforward approach to represent the accumulated intensity of scattered wave signals onto the spatial domain according to appropriate definition of wave-paths. The sum of the distance from an actuator to a damage and the distance from the damage to a sensor retains a constant in accordance with a specific wave speed, thus the locus of the possible solution becomes an ellipse with the actuator and the sensor as the foci. This approach is initially proposed by Wang et al. [4] in 2004. Their work was accounted for in the context of time-reversal, but it has been typically categorized in TOA concept. They

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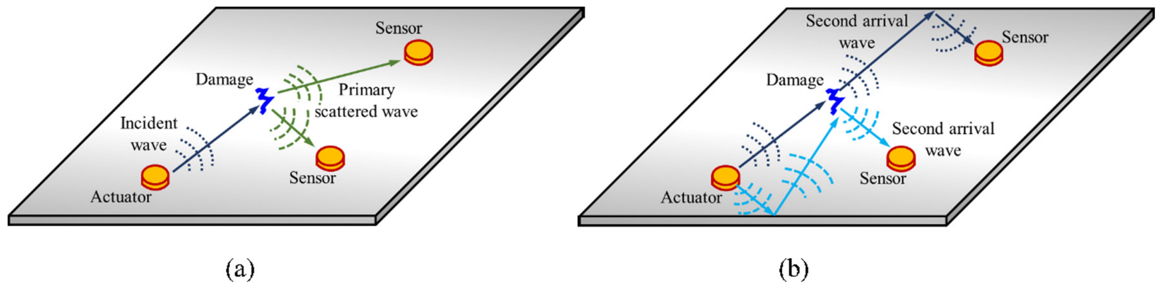

Fig. 1. Incident wave emitted from a piezoelectric wafer bonded on the plate surface, and the rest of wafers sensing (a) the primary scattered waves from the damage and (b) the second arrival waves.

basically applied unit weighting coefficient about each image pixel, yet Michaels et al. [5] enhanced the algorithm by employing an exponential window to isolate the primary scattered waves. Furthermore, Hall and Michaels [6] proposed a variant on TOA-based algorithm applying adaptive weighting coefficients for each image pixel; the optimal weightings are estimated so as to minimize the overall image values while preserving the value at the damaged location under an assumption that at a specific location. However, it is still unfree from the effects on the artifacts, since the multiple wave-paths are not taken into account in their algorithm. Recently, in Ch. 9 of [7], Michaels discussed about the methodologies to compensate the baseline data in the TOA-based damage imaging algorithms under environmental and operational changes. Time difference-of-arrival (TDOA), which is based on hyperbola algorithm, is another popular damage imaging technique. Even though, in TDOA, the number of possible combinations of sensor pairs increases compared to that of TOA, TDOA-based damage imaging approach does not overly enhance the quality of the image compared to TOA [8,9]. Therefore, this paper focuses its attention on TOA-based damage imaging algorithm for precise damage localization with limited number of piezoelectric wafers. In addition, it is worth noting that these approaches only consider the primary scattered waves.

Damage imaging algorithm, in practice, encounters challenges in the damage localization due to the presence of multiple wave-paths arising from interacting with geometric features of the structure. Historically, multiple wavepaths were often ignored or treated as a nuisance in locating the damage. However, these wavepaths that contain the scattered waves from the damage can carry some information about the damage, even though the magnitude of the waveforms is smaller than the primary scattered waves. Recently, many researchers began to pay attention to the usage of the multiple wavepaths for the damage imaging. For instance, Hall and Michaels [10] implicitly utilized multiple wavepaths of scattered waves for the wavefield data that was measured in advance by using permanently attached piezoelectric wafers as actuators and a laser vibrometer as a movable sensor, thus the estimated scattered waves are compared to monitoring scattered wave. Even if this represented significantly improved image compared to the minimum variance imaging [7], it may not be practical for SHM to capture the wavefield data while in operation. A probabilistic model was employed by Flynn et al. [11] to localize damages in a plate-like structure, where they discussed about the possibility that can improve their imaging algorithm by involving the multiple wavepaths. Ebrahimkhanlou et al. [12], recently, explicitly employed the multiple wavepaths to estimate the scattered waves prior to monitoring the structural health of a metallic plate; the pre-estimated set of scattered signals is compared to the monitoring signals with correlation function at each spatial coordinate. Yet it still requires a priori information of scattered wavefield. In this article, multiple wavepaths in a rectangular plate are explicitly defined in order to use for an enhanced damage imaging algorithm that incorporates these wavepaths. To realize this, it is essential to consider a proper signal decomposition method to separate the individual wave packets accurately.

A majority of waveforms measured from sensors for practical structures involves multiple wave packets with time-varying features, thus more advanced signal processing techniques are required to deduce the meaningful information from the received signals. Most existing methods, such as short time Fourier transform (STFT) [13,14], wavelet transform (WT) [15,16], Wigner-Ville distribution (WVD) [13,17], and matching pursuit (MP) [18,19] algorithm, seek for the correlating relations of the signal to the basis functions. Among these decomposition techniques, MP algorithm introduced by Mallat and Zhang [18] is an iterative greedy approach, that can decompose any signal into a linear combination of waveforms chosen with an adaptive process from a redundant dictionary of basis functions – so called atoms. As long as the dictionary properly encompasses the properties of the wave to be analyzed, it can extract the intrinsic features, such as time of flight, frequency, frequency modulation, and so on, of the given signal accurately. It is also worth of mentioning about the noise robustness in MP algorithm. MP method can decompose features of a signal regardless of existence of ambient noises because it only refers to the pre-defined atom functions which is normally not relevant to the environmental noise. This is a very attractive feature of MP method in that most signals in real field are contaminated by unwanted noise.

For MP algorithm, it is an essential process to define a proper set of atom functions in a dictionary to extract features of a signal accurately. In past decades, even though MP method has been addressed by many researchers for SHM applications, the atom functions in many studies have been mostly designed based on the heuristic Gaussian windowed functions. Hong et al. [20] implemented a signal decomposition for non-dispersive wave using the Gabor dictionary. Raghavan and Cesnik [21] and Xu et al. [22] made use of Gaussian chirp dictionary to simulate dispersion of Lamb wave. However, the application of the Gaussian based dictionaries can be limited for the specific waveform such as Hann-windowed toneburst. In this article, a new dictionary that is capable of accurately imitating the wave propagation induced by the Hann-windowed toneburst excitation, is proposed, of which convergence and accuracy is validated through simulation study, and is shown to be superior to the typical Gaussian based dictionaries. Finally, MP with the proposed dictionary is applied for the experimental signals in order to decompose the individual wave packets – the primary as well as the second arrival waves (Fig. 1). The decomposed wave packets are employed for the proposed damage imaging algorithm; thus it can localize damages more robustly with stronger intensity of image with only three or four piezoelectric wafers.