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# A guided wave dispersion compensation method based on compressed sensing

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ABSTRACT

The ultrasonic guided wave has emerged as a promising tool for structural health monitoring (SHM) and nondestructive testing (NDT) due to their capability to propagate over long distances with minimal loss and sensitivity to both surface and subsurface defects. The dispersion effect degrades the temporal and spatial resolution of guided waves. A novel ultrasonic guided wave processing method for both single mode and multi-mode guided waves dispersion compensation is proposed in this work based on compressed sensing, in which a dispersion signal dictionary is built by utilizing the dispersion curves of the guided wave modes in order to sparsely decompose the recorded dispersive guided waves. Dispersion-compensated guided waves are obtained by utilizing a non-dispersion signal dictionary and the results of sparse decomposition. Numerical simulations and experiments are implemented to verify the effectiveness of the developed method for both single mode and multi-mode guided waves.

## 1. Introduction

Ultrasonic guided waves, such as Lamb waves, have received considerable attention because of their powerful properties, such as high sensitivity to various types of damage, and the capacity of monitoring a large area while a sparse sensor array is used for damage detection. Therefore, guided waves appear to be very crucial in nondestructive testing (NDT) [1,2] and structural health monitoring (SHM) [3–5]. In the past decades, many important applications of guided waves in engineering are proposed in various fields. Some examples including aluminum structures [6,7], pipes/axles [8], and carbon fiber reinforced composite laminates [9–11] have validated the effectiveness of the guided wave based method for damage detection. In the field of guided wave based SHM, a common system configuration uses a sparse array of mounted or embedded sensors in structures to excite or record guided waves. In most SHM damage detecting algorithms, such as delay-and-sum (DAS) [12] method, minimum variance distortionless response (MVDR) [13] method, and correlation-based [14,15] methods, the reference guided waves should be acquired to serve as the baseline for damage detection. Therefore, only the residual signals, the results of subtracting the baseline signals from the recorded signals, are used in those algorithms.

The guided waves registered from structures, for example, aluminium plates, are usually complicated. Except the portions caused by the geometric characteristics, such as edge reflections, there exist at least two guided wave modes at any

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frequency in plate like structures, known as multi-mode characteristic. Furthermore, since the frequency dependence of guided wave velocities, even in a plate of equal thickness, the recorded guided waves will disperse either in time or space, which is referred to as dispersion. When the propagation distance increases, the dispersion effect will be more serious. As the consequence of multi-mode and dispersion effect, the wave packets will overlap with each other degrading the temporal resolution of the guided waves and making the signals hard to be interpreted. For multi-mode, dispersion effect can be compensated or suppressed by selecting the special excitation center frequency [16] or using a mode selection technique [17–19]. Therefore, the methods of dispersion compensation or dispersion removal should be developed.

The simplest method to suppress the dispersion is to use narrowband excitation [20], usually a windowed tone burst centered at a certain frequency. In such frequency bandwidth, the group velocity is small fluctuation with respect to frequency. However, the time width and frequency bandwidth cannot be decreased simultaneously. When frequency bandwidth decreases, the dispersion effect decreases, but the temporal resolution also decreases. Furthermore, the dispersion effect will increase when propagation distance increases. Wilcox [21] proposed a rapid signal processing technique to compensate the dispersion effect by making use of a priori knowledge of the dispersion curves of the structure, which is referred to as the time-distance mapping method. It transforms the dispersive guided waves from time domain to frequency domain, then interpolates to wavenumber domain and finally maps signals to distance domain. The method is based on the fact that the dispersion compensated signals can be obtained by propagating backward the recorded signals to its source. Although it is a popular dispersion compensation method, the waveform of each wave packet after compensated is deformed and not identical with the original excitation. Liu and Yuan [22] proposed a linear mapping technique for dispersion removal based on Taylor linear approximation of wavenumber. The linear mapping performed the dispersive signals in wavenumber domain to transform the nonlinear dispersion relation into the linear one by truncating the Taylor expansion into linear term which is nondispersive. Xu et al. [26] compared the above two methods, dispersion compensation(the time-distance mapping method) and dispersion removal, and drew a conclusion that the dispersion removal method outperformed the dispersion compensation method but the former was not able to directly get the spatial locations of the wave packets. De Marchi et al. [23,24] presented a guide wave dispersion compensation method, referred to as the warped frequency transform (WFT), which maps frequency domain into "frequency warped" domain by a warping function. However, the compensated signal is still deformed compared with the excitation because of the nonlinearity of the warping function [25]. Recently, Luo et al. [27] analyzed the reason of waveform deformation in the time-distance mapping method, and developed a reshaped excitation dispersion compensation method by generating a reshaped excitation. The reshaped excitation was carefully developed according to the original excitation and group velocity. However, the above methods only work efficiently under the situation that only one mode exists in wave propagation. For multi-mode cases, the target mode guided waves can be compensated completely, but the non-target modes will be compensated partly or become even more dispersive.

As a theory of having the capability to deal with signal sparse decomposition and reconstruction, compressed sensing (CS) [28,29] has attracted great interest in the field of guided wave based signal processing. Based on the sparse prior of the guided waves in a specified dictionary, some sparse reconstruction algorithms have been developed to process guided waves. Mor et al. [30] proposed a support matching pursuit (SMP) method for approximating overlapping ultrasonic echoes based on a Gabor dictionary. The results showed that the SMP method can separate overlapping echoes, and it can achieve superior performance than matching pursuit (MP) and basis pursuit (BP) method. Tse and Wang [31] used MP for reconstruction of defect reflection signals in pipes with an optimized dictionary based on two interfering reflection. Harley and Moura [32] showed the capability of the orthogonal matching pursuit (OMP) in recovering dispersion curves from guided wave data. Mesnil and Ruzzene [33] developed a CS technique through $l1$-minimization for the sparse reconstruction of guided wavefields. In [34], Perelli et al. proposed a WFT based CS method for guide wave damage localization. Through this method, the sparse reflectivity function in distance domain can be recovered from the dispersive guided waves, which improves the accuracy of wave propagation distance estimation. In [35], Perelli et al. used the WFT and wavelet packet to generate the best basis for a sparse representation of dispersive guided waves. In [36], De Marchi et al. used a BP algorithm combined with a warped dictionary, which has the potential to match each mode guided waves, to extract the distance of guide wave propagation. Through building different sparse representation models and constructing the corresponding dictionaries, different results can be achieved for guided waves, such as feature extraction, wavefield reconstruction, and echo separation, as mentioned above.

To address the problem of dispersion compensation for both single mode and multi-mode guide waves, a new method based on CS is presented in this paper. This method leverages the assumption of sparsity of the number of wave packets with respect to the number of sampling points, and uses the powerful sparse decomposition and reconstruction techniques to implement dispersion compensation. In order to implement sparse decomposition, the developed method builds a dispersion signal dictionary by utilizing the dispersion characteristic of the guided wave modes firstly. Each atom of the dispersion signal dictionary corresponds to a dispersive guided wave which dispersively propagates a certain distance. Secondly, the compensated guided waves are reconstructed using the results of sparse decomposition and a non-dispersion signal dictionary, which is built by the non-dispersion relation of the inspected structure. Results show that the developed method can compensate the dispersive guided waves for both single mode and multi-mode.

The following sections are organized as follows. In Section 2, the time-distance mapping method is reviewed and discussed. In Section 3, the methodology of the proposed dispersion compensation method is presented. The numerical simulation and experimental verification are presented in Sections 4 and 5, respectively. In Section 6, conclusions are given.