Journal of Sound and Vibration 367 (2016) 22–36

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Dispersion analysis for broadband guided wave using generalized warblet transform

Y. Yang [a], Z.K. Peng [a,*], W.M. Zhang [a], G. Meng [a], Z.Q. Lang [b]

[a] The State Key Laboratory of Mechanical System and Vibration, Institute of Vibration Shock & Noise, Shanghai Jiao Tong University, Shanghai 200240, PR China

[b] Department of Automatic Control Systems Engineering, University of Sheffield, Mappin Street, Sheffield, UK

ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
5 December 2015
Accepted 19 December 2015
Handling Editor: L.G. Tham
Available online 8 January 2016

Keywords:
Broadband wave
Highly dispersive
Multi-modal wave
Generalized warblet transform
Mode isolation

ABSTRACT

Dispersive properties of guided waves (GW), which indicate the group velocity of the wave varies with the frequency, have been widely investigated in many applications. The broadband GW is usually highly dispersive and multimodal, which is a good candidate for time–frequency analysis (TFA). In the time–frequency (TF) domain, the dispersion trajectory of a dispersive single-modal wave, which is a function of frequency, corresponds to its frequency-dependent dispersion law. To analyze such highly dispersive and multi-modal broadband guided wave (HDMB-GW) effectively, we proposed a generalized warblet transform (GWT) based TFA method, which comprises the GWT and a mode separation procedure. Advantages of the proposed method include distinguishing and obtaining the dispersion trajectories of highly dispersive and overlapped modes of the HDMB-GW in the TF domain. Comparing with the existing TFA methods, the proposed method is more suitable for the HDMB-GW, especially when the dispersion trajectories of different modes intersect with each other. Both the simulated and experimental analysis on Lamb waves verified the effectiveness of the proposed method in the dispersion analysis for the HDMB-GW.

1. Introduction

Guided waves, which are mechanical stress waves propagate in waveguide guided by its boundaries, are famous for the ability of traveling a long distance with little loss in energy. Such merit allows GWs to be widely applied in structure health monitoring [1–3] and non-destructive integrity evaluation [4,5]. The underlying principle is that GWs traveling through the different structure or region change their characteristic, e.g., amplitude, phase, dispersion and time-of-flight [6]. Dispersion and multimodes are two important properties of the GW, which are strongly related to the structure of the waveguide. The former means the group velocity of the GW varies with frequency. The latter indicates the GW have multiple modes that are discriminated based on the propagation fashion in the waveguide, i.e., symmetric and anti-symmetric modes.

In most cases, narrow-bandwidth and single-modal GWs are usually considered to ignore the dispersion effect. Specifically, a narrow-bandwidth wave packet with the selected center frequency is used as the excitation. In the detected GW signal, the mode of a wave packet is determined by estimating the arriving time of the center of the wave packet. The

* Corresponding author.
E-mail addresses: emma002@sjtu.edu.cn (Y. Yang), z.peng@sjtu.edu.cn (Z.K. Peng), wenmingz@sjtu.edu.cn (W.M. Zhang), gmeng@sjtu.edu.cn (G. Meng), z.lang@sheffield.ac.uk (Z.Q. Lang).

http://dx.doi.org/10.1016/j.jsv.2015.12.037

arriving time is estimated according to the theoretical dispersion curve of this mode at the very specific frequency. The energy and arriving time of the identified wave packet are two critical quantities that are utilized for the defect detection. By taking advantage of narrow-banded GW, piezoelectric transducer array is adopted to localization the defect [7,8], scanning laser dropper vibrometry and shearographic enable the measurement of a full wavefield of GW [9,10].

On the other hand, broadband GWs, carried dispersion information of multimodes, have attracted increasing attention. The dispersive properties have been widely investigated in various applications, i.e. Lamb wave or shear-waves in non-destructive evaluation (NDE) and structure health monitoring (SHM) [11–14], GWs in underwater target characterization and vibroacoustic analyses [15–17], GWs in bone health assessment [18–20], etc. The dispersion analysis of the GW benefits the feature extraction for fault diagnosis, the knowledge acquisition for wave propagation, as well as the parameter estimation for the tested material. GWs traveling through the different structure or region change their characteristic, e.g., amplitude, phase, dispersion and time-of-flight. For example, the energy associated to the dispersion curves varies in different structures or regions [21].

In order to acquire the knowledge about the structure, the dispersion of GWs have been modeled for various structures [22–27]. The shortcomings of the dispersion analysis based on GW modeling are (1) the different models have to be set up for different structures. Even for the same structure, the models could be different due to the material variation, (2) it is difficult to construct models for complicated structures. The signal processing based dispersion analysis, on the other hand, provides a more straightforward solution for various structures and can be carried out for complicated structures.

In this paper, the broadband GW is described as the highly dispersive and multimodal broadband GW (HDMB-GW). The complexity of the HDMB-GW makes it a good candidate for time–frequency analysis (TFA). For a broadband dispersive single-modal wave, the ridge in the TF representation is called dispersion trajectory, which is an important TF feature corresponding to the dispersion law of the wave. For the HDMB-GW, ridges in the TF representation is dispersion trajectories of different modes, each of which varies nonlinearly with the frequency and overlaps with others at certain frequency.

Non-parametric TFAs adopted to analyze GWs include short-time Fourier transform (STFT) [16,18,28], wavelet transform [12,14,21,29,30], S transform [31] and Wigner–Ville distribution (WVD) [32]. Owing to the fixed TF resolution, the STFT cannot characterize the highly dispersive GW accurately. The multi-resolutions of the wavelet transform and S-transform, which means the better frequency resolution but worse time resolution at low frequency, and the better time resolution but worse frequency resolution at high frequency, are also not suitable for the HDMB-GW. These linear non-parametric TFAs, which are based on the window analysis, suffer from the poor energy concentration due to the limited TF resolutions. As a typical bilinear TFA, the WVD based on the global Fourier transform generates the best concentration for the auto-terms, but introduces plenty of cross-terms in the case of the HDMB-GW. To focus the energies and suppress cross-terms effectively, several post-processing methods have been developed for conventional non-parametric TFAs. Radon transform [33–35] was used to suppress the cross-terms of the bilinear TFA. It is suitable to analyze waves with linear dispersive trajectories, but it will distort the nonlinear dispersion trajectories of the HDMB-GW. Reassignment technique was introduced to enhance readability of TF representations [36–40]. By reassigning the TF representation, the dispersion trajectory could be distort and even worse with the presence of noise. Besides, it cannot avoid the interferences of the cross-term between multiple modes.

To analyze the HDMB-GW effectively, various parametric methods have been proposed. Kuttig et al. [41] applied the chirplet to fit the dispersion trajectory of the wave mode adaptively, aiming to extract features of a single mode from the HDMB-GW. To ensure a reliable analysis of the wave mode, they ignored the cases that the dispersion trajectories of modes are overlapped. Zhao et al. [42] adopted the chirplet decomposition to investigate the dispersion of the concerned modes for the HDMB-GW. Raghavan and Cesnik [43] developed a chirplet matching pursuit based method for GW based SHM. Zhang et al. [44] addressed the recent accomplishment of the sparse signal representation for ultrasonic NDE signals. The basis functions of the sparse representation include Gaussian function, Morlet wavelet and chirplet function [45]. The above methods focus on the local characterization of the mode with linear dispersion trajectory and ignore the case of the crossed dispersion trajectories. Searching the properly matched chirplets from a redundant dictionary is often time-consuming especially for the HDMB-GW with the presence of the noise. Except the above sparse representation, several parametric TF transforms have been developed for the HDMB-GW. Hong et al. [46] proposed a dispersion-based short-time Fourier transform (D-STFT). With an extra rotating parameter, it approximates the dispersion trajectory with the 2-order polynomial in the TF domain. When the wave has high-order dispersion trajectory, the D-STFT will distort the wave in the TF domain.

Another group of parametric methods takes advantages of the idea of dispersion compensation [47]. The dispersion compensation is to convert a dispersive wave signal to be a wave pulse by removing the dispersion effect. Then, the compensated signal can be well analyzed by any non-parametric TFA. The dispersion compensation algorithm requires the predicted dispersion curves to realize the fully compensation. Warped frequency transform (WFT) [48] and frequency domain polynomial chirplet transform (FPCT) [49] are two typical methods belonging to this category. The WFT first unwarps the dispersive signal, and then wraps TF points of the STFT of the signal to obtain a dispersion-matched warpogram. The warpogram might have TF points without amplitudes due to the warping of the STFT. The FPCT adopts a rotation operator, which rotates the dispersion trajectory, and a shift operator, which shifts the windowed phase of the rotated signal. The WFT and FPCT are similar in two aspects: (1) both the unwarping and rotation are equivalent to the dispersion compensation; (2) both of them are appealing to present a TF representation with a more flexible tiling of the TF domain. The implementation of the WFT is different from the FPCT as the former contains two separated procedures and the latter is a single transform with two built-in operators. Besides, the former uses the predicted dispersion curve to compensate and warp directly, while the FPCT uses the polynomial kernel approximated the predicted dispersion curve to rotate and shift.