NDT&E International 74 (2015) 15–23

Contents lists available at ScienceDirect

NDT&E International

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

Mode separation and characterization of torsional guided wave signals reflected from defects using chirplet transform

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ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form
7 April 2015
Accepted 24 April 2015
Available online 5 May 2015

Keywords:
Mode separation
Chirplet transform
Reflection coefficient
Defect characterization
Magnetostrictive sensor

ABSTRACT

The sensor configuration of a magnetostrictive guided-wave system can be described as a single continuous transducing element which makes it difficult to separate the individual modes from the reflected signal. In this work, we develop the mode decomposition technique employing chirplet transform, which is able to separate the individual modes from dispersive and multimodal waveforms measured using the magnetostrictive sensor, and estimate the time–frequency centers and individual energies of the reflection, which would be used to locate and characterize defects. The reflection coefficients are calculated using the modal energies of the separated modes. Experimental results on a carbon steel pipe are presented, which show that the accurate and quantitative defect characterization could be enabled using the proposed technique.

1. Introduction

Methods that apply guided wave technology for pipeline screening purposes have seen important technological improvements in the past years [1], gaining more and more popularity amongst industrial users. Much progress and many advancements have been made for the application of guided waves in inspecting pipelines. However, the quantitative evaluation of defect sizes or severity is always a challenging task in NDT after a pipe defect has been found because of the complexities involved in the reflection signal [2]. The scale of difficulty is magnified in real practices as the reflected waves are subjected to contamination from a diverse range of noise sources. Such sources could be randomly generated environmental noise and unexpected modes from mode conversion as well as the reverberation of waves. Insufficient defect information prevents an accurate indication of damage severity without applying additional testing or direct measurement. In order to carry out a maintenance remedy on defective pipelines properly and efficiently, the ability to characterize pipeline defects is very important, particularly for cases in which the locations of defects are difficult to access, such as buried pipelines or pipelines inside walls.

Although axisymmetric modes such as longitudinal or torsional modes are incident on pipes, mode conversion to non-symmetric modes such as flexural modes could occur at non-axisymmetric defects. The conversion is dependent on the similarity in particle motion of the incident and mode-converted modes. Unfortunately, these modes are generally dispersive and their group velocities are very close to those of the incident mode. Both facts complicate the use of guided waves for inspection tasks. Dispersion affects guided modes by increasing wave-packet duration and decreasing amplitudes, and even overlapping modal packets together in general. This would impair resolution in space and time, and weaken the detectability at the receiver [3].

Some transducer techniques have been developed to excite specific guided modes while restraining others, such as a guided wave focusing system with phased array [4] and magnetostrictive sensors [5]. The circumferential location and length could be determined very accurately using the array systems. However the wave focusing is extremely time consuming for full coverage of the pipe wall and requires extensive hardware since separate signal generation and amplification are required for each transducer in the array. Also, using these techniques cannot completely suppress the dispersion in recorded responses. On the contrary, dispersion actually contains rich information of waveguide properties and it is thereby a diagnostically useful feature of guided waves, and is specially preferred for many applications [6–9]. In particular, reflection coefficients [10] have been widely used to quantitatively evaluate the defect sizes in pipelines, which are based on the comparison of the magnitudes of the non-axisymmetric modes with those of the axisymmetric modes. There is thus a clear call for methods of signal processing to extract and analyze individual dispersive waveforms from dispersive multimode signals.

Conventional solutions to the problem of signal processing for guided waves are usually in the form of a number of

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http://dx.doi.org/10.1016/j.ndteint.2015.04.006
0963-8695/

time–frequency representations (TFR) [11,12], such as the short-time Fourier transform (STFT). The basic idea involves cutting a signal into short-interval segments by a sliding window and obtaining the variant distribution of the energy spectrum as a function of time. Various improved strategies have been developed for the purpose of guided wave signal analysis, such as reassignment time–frequency representation [7], dispersion-based STFT [13], match representation [14], and warped frequency transform [9], etc. These methods strongly enhance the resolution of dispersive energy representation and weaken modal interaction. Recently Tse and Wang [15] proposed a matching pursuit method to decompose the edge reflection signals and to evaluate the axial length of the pipe defect. The method efficiently resolved the closely spaced reflection components; however it was applied only to the axisymmetrical defects at which no mode conversion occurs.

A number of studies have also focused on mode separation in time and space. Hayashi and Kawashima [16] proposed a single mode extraction based on two-dimensional fast Fourier transform (2D-FFT) [17]. Recently, exploiting the benefit of the multi-emitter and multi-receiver, the singular vector decomposition (SVD) [18] has been successfully applied to obtain a guided mode vector basis, which can be further used to extract phase velocities. However, a large number of closely spaced transducers are needed to avoid aliasing and sophisticated multi-channel data capture and processing hardware to implement this approach for guided waves.

In order to separate individual guided modes in one measurement, Huang et al. attempted an empirical mode decomposition method [19], but they did not achieve good results because multiple modes usually occupy the same frequency band and intersect each other in time. An adaptive chirplet-based method has also proved to be an effective way to individually separate modal time–frequency atoms, so-called chirplets, from a multi-mode signal, and to qualify the energy of the individual mode [8]. Raghaven and Cesnik [20] proposed a new approach to separate overlapping multimodal reflections using chirplet matching pursuits and mode correlation.

The chirplet transform, a generalization of both the wavelet and the short-time Fourier transform, enables the extraction of components of a signal with a particular instantaneous frequency and group delay. The term "chirplet transform" was introduced by Mann et al. in 1991, for a new TFR, a generalization of the spectrogram and scalogram with additional degrees of freedom for time and frequency shear. While the chirplet transform allows for the decomposition of time domain signals into well-localized components (time–frequency atoms) with a constant chirp rate (that is, linearly changing instantaneous frequency), the resulting representation is of dimension five. This complicates the visualization, computation, and interpretation of a transformed signal. In order to reduce the complexity of the problem, researchers have considered subspaces of only the five-dimensional parameter space [21], employed a matching pursuit algorithm [22] and utilized a dispersion-based chirplet transform for the analysis of dispersion curves from guided wave signals [13].

Reflection coefficients have been widely used to quantitatively characterize the defects in pipelines. Many researchers have investigated related issues through laboratory experiments and finite element simulations. For example, Alleyne et al. [23] and Demma et al. [24] reported that the reflection of incident modes, L(0,2) and T(0,1), are close to the linear functions of the circumferential extent and radial depth, respectively, of a defect. Bai et al. [25] used an efficient numerical procedure for the three-dimensional reflection problem to analyze how the length and depth of a circumferential defect affect the scattering characteristics in a pipe. Carandente and Cawley [26] studied the reflection of the fundamental torsional mode T(0,1) from 3D defects in pipes with different shapes and found that at a given maximum depth of a finite discontinuity, the peak of the reflection coefficient from a defect is linearly dependent on the circumferential extent of the defect and is independent of its shape.

The findings of these studies provide a useful foundation for further research. The sensor configuration of the magnetostrictive guided wave systems can be described in a simple way as a single continuous transducing element attached to the pipe and surrounding the circumference independently of the pipe size. With this configuration, it is difficult to separate the individual modes from the signal reflected from the defects, unlike the multi-element transducer ring of the piezoelectric systems. A signal processing method is thus required. The separated modes can be used to calculate the reflection coefficients for characterizing the defect size.

We thus introduce and utilize the chirplet transform based on the maximum likelihood estimation, which can be regarded as the selective mode separation. In order to acquire a signal reflected from the defect, experiments using magnetostrictive sensors were conducted on the pipe with circumferential defects. The chirplet transform is applied to the experimental signal to separate the dispersive signal into individual modes and to obtain the reflection coefficients for the defects using the modal energy. Finally, it is shown that accurate and quantitative defect characterization could become enabled using the reflection coefficients obtained from signal processing based on the chirplet transform.

2. Chirplet transform and its application

The chirplet transform was introduced as a generalized TFR by Mann and Haykin [27]. The basis function can be adjusted by means of shifting, shearing, and scaling operators, resulting in a five-dimensional parameter space for the energy density which comprises projections of the respective densities obtained from a short-time Fourier transform (time and frequency shift) and a wavelet transform (time shift and scaling); a comparison is shown in Fig. 1. Fig. 1(a) represents the generation of the STFT and wavelet transforms by introducing the operators which allow arbitrary time and frequency shifts, and scale. Modulation with a chirp in the time domain ($\mathbf{Q}_q$) shears the time–frequency atom in the frequency direction and modulation with a chirp in the frequency domain ($\mathbf{P}_p$) shears in the time direction. The shear parameters p and q determine the slope of the semi-axes of the chirplet atom ellipses.

2.1. Definition of the chirplet transform

The standard definition of the chirplet transform is given by the inner product of a basis function $g(t)$ and the signal $x(t)$:

$$C^{ct}(t_0,\ \omega_0,\ s,\ q,p) = \int_{-\infty}^{\infty} x(t) g^{*}_{t_0,\omega_0,s,q,p}(t)dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} X(\omega) G^{*}_{t_0,\omega_0,s,q,p}(\omega)d\omega \quad (1)$$

where $*$ denotes the complex conjugate. The basis function $g(t)$ and its Fourier transform $G(\omega)$ belong to a family of chirp signals:

$$G_{t_0,\omega_0,s,p,q}(\omega) = \mathbf{T}_{t_0}\mathbf{F}_{\omega_0}\mathbf{S}_s\mathbf{Q}_q\mathbf{P}_p H(\omega),$$
$$g_{t_0,\omega_0,s,p,q}(t) = \mathbf{T}_{t_0}\mathbf{F}_{\omega_0}\mathbf{S}_s\mathbf{Q}_q\mathbf{P}_p h(t), \quad (2)$$

where the operators $\mathbf{T}_{t_0}$, $\mathbf{F}_{\omega_0}$, $\mathbf{S}_s$, $\mathbf{Q}_q$, and $\mathbf{P}_p$ act in the manner represented in Table 1 on the window function or its Fourier transform, respectively.

Signal components that are concentrated in the time–frequency domain at a location specified by the parameters t_0, ω_0, s, q, and p can be extracted by performing a chirplet transform. Analogous to the spectrogram and scalogram, the energy