Signal Processing 96 (2014) 21–28

Contents lists available at ScienceDirect

Signal Processing

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

# Structure damage localization with ultrasonic guided waves based on a time–frequency method

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ARTICLE INFO

*Article history:*
Received 20 November 2012
Received in revised form
3 April 2013
Accepted 27 May 2013
Available online 7 June 2013

*Keywords:*
Ultrasonic guided wave
Time–frequency analysis
Wigner–Ville distribution
Damage localization
Damage imaging

ABSTRACT

The ultrasonic guided wave is widely used for structure health monitoring with the sparse piezoelectric actuator/transducer array in recent decades. It is based on the principle that the damage in the structure would reflect or scatter the wave pulse and thus, the damage-scattered signal could be applied as the feature signal to distinguish the damage. Precise measurement of time of the flight (TOF) of the propagating signal plays a pivotal role in structure damage localization. In this paper, a time–frequency analysis method, Wigner–Ville Distribution (WVD), is applied to calculate the TOF of signal based on its excellent time–frequency energy distribution property. The true energy distribution in the time–frequency domain is beneficial to reliably locate the position of damage. Experimental studies are demonstrated for damage localization of one-dimensional and two-dimensional structures. In comparison with traditional Hilbert envelope and Gabor wavelet transform methods, the proposed WVD-based method has better performance on the accuracy and the stability of damage localization in one-dimensional structure. In addition, the proposed scheme is validated to work effectively for damage imaging of a two-dimensional structure.



## 1. Introduction

The ultrasonic guided wave has been widely acknowledged as an effective approach for structure damage identification and health monitoring in recent years. Conventional guided wave techniques always need bulky and complicated instruments as well as much human interference. For example, ultrasonic probes could generate or collect guided wave with excellent precision and controllability. However, they always need couplant between the probes and the structure surface to be detected, which would bring great interference into the system. Electro-magnetic acoustic transducers (EMATs) could generate shear horizontal mode guided wave effectively and realize non-contact detection, but their applications are normally limited to magnetic materials. Laser-based ultrasonic instruments have high resolution and great precision, but the high cost of the equipment limits its application in engineering [1,2]. As the technology of piezoelectric materials develops, the combination of ultrasonic guided wave and spare piezoelectric actuators or transducers becomes more applicable to this area with the merits of low cost, full range, easy integration, wide frequency response, etc. [2,3]. Several aspects have been taken into study by recent researchers, such as the damage degree assessment against the amplitude changes of the guided wave, excitation of the effective wave mode, localization of the damage, and optimal distribution of the piezoceramics patch array. Both numerical and experimental studies have been conducted in the past decade [4–11]. This paper focuses on the structure damage localization with ultrasonic guided wave provided by the piezoelectric actuators.

The basic principle of the method for structure damage localization could be described as below [8,9]: the guided wave pulse is put into the structure with the piezoceramics patch bonded on it and collected by another piezoceramics patch. If there is damage in the structure, the

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http://dx.doi.org/10.1016/j.sigpro.2013.05.025

propagating guided wave in the structure would be reflected or scattered by the damage. In order to distinguish damage, the difference signal is acquired by the subtraction of the damaged guided wave signal with the damage-free signal, and it is the feature signal that carries the damage information. Based on the difference signal, the structure defect could be detected by geometry localization or imaging demonstration through different paths of the piezoceramic array. For the structure damage localization, no matter the geometrical or imaging method, the key point in the process is to define the arrival time of the signals and acquire the time of the flight (TOF) of the signals. They directly determine the precision of the localization.

The approach based on acquisition of the difference signal is reliant on defects causing a measurable change in the scattering. Its success depends on how to analyze the residual signal after the subtraction. The difference signal is always rather weak because the propagation of the ultrasonic guided wave in the structure is rather complicated with the property of multiple modes, frequency dispersion and the reflection interruption from the borders. Low signal-to-noise ratio (SNR) of the difference signal always causes a great error for the calculation of the TOF of the signal. And it would further influence the damage localization in the structure. The traditional methods to calculate the TOF of the propagating signals mainly include the thresholding value method, correlation coefficient method, Hilbert envelope method and wavelet transform method. Ref. [10] realizes the guided wave-based pipeline defect characterization with the correlation coefficient to calculate the TOF of the feature signal. Refs. [9,12] utilize Hilbert envelope to define the arrival time of guided wave signal and explore the damage imaging of plate structure based on a PZT array. Damage detection in plate structure based on the Gabor wavelet transform method is explored in Ref. [11]. These methods may not locate the damage precisely and stably for rough time estimation due to the interruption of noise or approximate energy distribution (e.g., wavelet transform). Moreover, time–frequency analysis has been widely used for structure health monitoring based on its excellent ability to analyze non-stationary signal [13–15], and as well it is verified to be quite effective to deal with guided wave signal [16–18]. Researchers have applied time–frequency analysis to various aspects on the guided wave technique, e.g., analyzing the frequency diversion property of guided wave [16], estimating the arrival time of certain wave modes [17,18] and evaluating the degree of structure damage [18]. On the structure damage localization, current studies mainly use the damage information distributed in the time–frequency domain as the diagnostic evidence. However, there is still further work to be discussed on how to improve the accuracy by using the property of time–frequency analysis. In addition, currently there are little works addressing on the structure damage imaging based on time–frequency analysis.

This paper considers employment of true time–frequency energy distribution for improving the localization accuracy of structure damage by combining the ultrasonic guided wave approach with the Wigner–Ville Distribution (WVD) method. The proposed scheme is based on the excellent merit of the WVD in exhibiting true time–frequency energy distribution. It has the anti-noise property and can reveal true energy distribution of the damage, so it is supposed to outperform current Hilbert envelope and wavelet transform methods in estimating the TOF of the guided wave signal. This paper first presents the WVD-based principle of damage localization in one-dimensional structure. Furthermore, a feature function, which is extracted from the time–frequency distribution, is applied as the fundamental of the damage imaging algorithm for two-dimensional plate structure. The rest of this paper is organized as follows. The theoretical background of the proposed study is introduced in Section 2. In Section 3, the experimental studies are set up to verify the proposed scheme on a one-dimensional structure for damage localization and a plate structure for damage imaging. Finally, conclusions have been remarked in Section 4.

## 2. Theoretical background

### 2.1. Principle of the WVD-based method

As introduced before, the TOF plays an important role in localization of the structure damage. Furthermore, choosing a proper baseline to distinguish the arrival time of the guided wave pulse is the pivotal step of calculating the TOF. This paper applies the method of time–frequency distribution (TFD) to define the arrival time of signal. Since the TFD can exhibit the signal energy in the time–frequency domain, so we can achieve a better knowledge on how the energy is changed along the time.

To get the TFD for a signal, various time–frequency analysis methods are available. The short-time Fourier transform (STFT) and the wavelet transform are two of many common methods. However, they can only express the approximate energy distribution in the time–frequency domain [19]. In this paper, the Wigner–Ville distribution (WVD) is employed based on the theory that WVD can well describe true time–frequency energy distribution of a signal [19]. The WVD is motivated by the time–frequency energy density which describes the signal's energy distribution in terms of both time and frequency. Mathematically, the WVD is computed by correlating the signal with a time and frequency translation of itself as expressed below [19]:

$$WV_x(t,\omega) = \int x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)e^{-j\omega\tau}d\tau \tag{1}$$

The WVD is a TFD of bilinearity, which is more suitable to analyze nonlinear and non-stationary signals.

Let $X(\omega)$ denote the Fourier transform of the signal $x(t)$, then from the time/frequency marginal property of WVD, we can have

$$\begin{aligned}\frac{1}{2\pi}\int_{-\infty}^{+\infty} WV_x(t,\omega)\,d\omega &= \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)\frac{1}{2\pi}\int_{-\infty}^{+\infty} e^{-j\omega\tau}\,d\omega\,d\tau \\ &= \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)\delta(\tau)\,d\tau = |x(t)|^2\end{aligned} \tag{2}$$

$$\begin{aligned}\int_{-\infty}^{+\infty} WV_x(t,\omega)dt &= \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)e^{-j\omega\tau}dt\,d\tau \\ &= \int_{-\infty}^{+\infty} e^{-j\omega\tau}\int_{-\infty}^{+\infty} x(t)x^*(t-\tau)dt\,d\tau = |X(\omega)|^2\end{aligned} \tag{3}$$