NDT&E International 79 (2016) 17–29

Contents lists available at ScienceDirect

NDT&E International

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

Waveform separation and image fusion for Lamb waves inspection resolution improvement

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ARTICLE INFO

Article history:
Received 28 January 2015
Received in revised form
4 October 2015
Accepted 17 November 2015
Available online 2 December 2015

Keywords:
Lamb wave
High resolution inspection
Waveform separation
Image fusion

ABSTRACT

To improve the resolution of Lamb wave inspection, a waveform separation and image fusion strategy is established. The integration of the adaptive Chirplet transform and the time-varying band-pass filtering provides a methodology for extracting interest waveforms from the overall Lamb wave signals. On this basis, image generation and image fusion is employed to establish a visual description of the overall health status of structures. The strategy could be still available even under the conditions where the dispersion characteristics of the structure cannot be correctly estimated and the reference signals are not accessible. The merits of the proposed strategy are demonstrated by an experimental example.

1. Introduction

Lamb wave inspection has attracted considerable attention because of the advantages including high sensitivity to changes in structural properties and capability of propagation over a significant distance [1]. It has been proven very efficient for inspecting plate- and pipe-like components [2–5]. However, the multimodal and dispersion characteristics make it difficult to analyze and interpret the received signals. Especially, due to dispersion, the duration of received signal increases and the amplitude reduces. Both effects are undesirable in an inspection system.

For a common practical situation where a defect is located in close proximity to another structural feature (e.g. damage or edge), the defect will only be detected if its reflection can be separately identified [6]. Actually, the duration of a received signal may be regarded as the sum of two terms after some particular propagation distances. The first one is the initial temporal duration of a wave-packet and the second is the increase in wave-packet duration due to dispersion [7]. To obtain useful data from a Lamb wave inspection system, it is customary to use narrowband excitations to minimize the dispersive effects [8]. Excite the transducer with a variety of tone burst signals of different center frequencies and widths, and then select the one that generates the response exhibiting the best mode purity with the shortest duration time domain pulses [9,10]. Particularly, the development of the chirp technique provides an efficient way for this optimization since multiple narrowband responses can be extracted from a single chirp response [11-13]. However, in narrowband excitations, a compromise is often made between the bandwidth of the input signal and its duration to minimize the duration of the received signal, as a result, the dispersion in the recorded responses cannot be suppressed completely and the interference between wave packets that reflected from different structural features (e.g. damage and edge) cannot be eliminated.

For this reason, several signal processing techniques have been developed to identify defects. One representative method is the time reversal method. Launching a wave, recording it at the receiver position, inverting it in time, and reemitting it by the emitter, the first emitted signal without any dispersion effect may be captured. Considerable effort has been focused on this direction [14-17]. However, the requirement of multiple emissions of the waves is a main disadvantage for these techniques, which may take a long time for the inspection [18]. The dispersion compensation algorithm is another promising method, which maps signals from time domain to distance domain by utilizing the prior knowledge of the dispersion. When the computed dispersion characteristics match the actual ones, the dispersion compensation algorithm can restore each reflected signal exactly [19,20]. An alternative is the dispersion removal algorithm. In this method,

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http://dx.doi.org/10.1016/j.ndteint.2015.11.006
0963-8695/

the linear mapping performed in the finite usable frequency domain is to transform the original *in priori* known dispersion relation into the linear dispersion relation, *i.e.*, truncated the polynomial up to the linear term which is non-dispersive [21]. The limitation of both dispersion compensation and removal algorithms is that a prior knowledge of the exact dispersion curves over the full bandwidth of the input signal is required. For practical applications, if the elastic material constants are unknown, there is no effective analytic approach and numerical techniques could be used to predict the dispersion curves.

Actually, the effect of dispersion is that the energy in a wave-packet propagates as different speeds depending on its frequency. From the viewpoint of signal processing, the frequency content of the dispersive wave-packet is time-varying. For this reason, if a proper time–frequency representation (TFR) method is used, the wave-packets which interfere with each other in the time/frequency domain may be separately identified in the time–frequency domain. Aiming at improving the testing resolution, a waveforms separation and image fusion strategy is established in this paper. Firstly, adaptive Chirplet transform (ACT) is employed for analysis of guided waves, *i.e.*, identifying the dispersive signal components and estimating their instantaneous frequencies (IFs). On this basis, a time-varying filter (*i.e.* Vold–Kalman filter) is introduced to extract the time-domain waveform of damage-scattered wave components from the overall Lamb wave signals. The integration of time–frequency representation and time-varying filter provides a methodology for separating waveforms reflected by closely spaced defects. Benefiting from that, the interferences between different wave components could be eliminated. With the application of the image generation and image fusion, a visual description of the overall health status of structures could be established.

The rest of this paper is organized as follows. In Section 2, the adaptive Chirplet transform is briefly reviewed, and the applicability and theory of the Vold–Kalman filtering are also introduced. In Section 3, the strategy for waveforms separation and image fusion is established. Moreover, its application process is illustrated by an experimental example in Section 4. In Section 5, the performance of the proposed strategy is investigated. Finally, conclusions are given in Section 6.

2. Theories

2.1. Adaptive Chirplet transform

Adaptive Chirplet transform (ACT) is a representative TFR tool [22]. Similar to short-time Fourier transform (STFT), ACT involves the inner product between the signal and chirp basis functions. The ACT of a real signal $x(t)$ is given as [23]

$$C_x(t,f,c) = \int_{-\infty}^{+\infty} x(t+\tau)\omega_{T_0}(\tau)e^{-j\pi c\tau^2}e^{-j2\pi f\tau}d\tau \quad (1)$$

t, f are the time and frequency indices, respectively. $\omega_{T0}(\tau)$ is the window function of length T_0, and centered at time $\tau=0$. c denotes the chirp rates of basis functions. ACT can be physically interpreted as the projection of the signal $x(t)$ on a set of atoms with different chirp rates [23]. When the chirp rate $c=0$, the ACT degrades into normal STFT. From this view, STFT can be considered as a special case of ACT [24]. In other words, ACT could provide a more flexible and effective TFR than STFT. When parameter c in formula (1) matches the chirp rate of analyzed signal, a concentrated TFR is obtained. Hence, the key issue is how to select the parameter c properly in each analysis window of ACT so as to clarify the ridge of the kth signal component.

A coarse-fine basis optimization method is developed to determine the parameter c, which comprises the following steps. Firstly, a coarse instantaneous frequency (IF), or ridge curve of the kth signal components roughly estimated using the default initial value, e.g. $c=0$. Then, ACT is applied to the Lamb wave signals. In each analysis window of ACT, the parameter c_i takes the chirp rate of above estimated IF

$$c_i = \left[IF(t_i+T_0/2) - IF(t_i-T_0/2)\right]/T_0 \quad (2)$$

where c_i is the chirp rate in the ith analysis window centered at t_i, $IF(t_i+T_0/2)$ and $IF(t_i-T_0/2)$ are the roughly estimations of IFs at $t_i+T_0/2$ and $t_i-T_0/2$, respectively.

In this way, the kth signal component appears with good concentration in the TFP produced by ACT. Hence, a more accurate estimation of IF could be obtained. Although the estimation error of coarse IF has some influence on determine of c, and consequently the refined IF, this effect could be alleviated significantly by repeating ACT one more time using the newly updated IF.

2.2. Vold–Kalman filter

Referring to [25], assuming a harmonic wave propagating in a plate, the displacement on the surface, $x(l,t)$, may be describe by a general analytic expression as,

$$x(l,t) = A(\omega)e^{j(\omega t - kl - \theta)} \quad (3)$$

where $A(\omega)$ is a frequency-dependent amplitude constant, $\omega=2\pi f$ is the angular frequency, the wave number $k=\omega/c$, c is the phase velocity, and θ denotes the phase. If the propagating distance, l, is fixed, the displacement, $x(l,t)$, is only time dependent, so Eq. (3) may be modified as,

$$x(t) = \left[A(\omega)e^{-j(kl+\theta)}\right]e^{j\omega t} = K(\omega)e^{j\omega t} \quad (4)$$

It satisfies the second-order ordinary differential equation (ODE),

$$\frac{d^2x(t)}{dt^2} + \omega^2 x(t) = 0 \quad (5)$$

the complementary solution of which is

$$x(t) = K_1 e^{j\omega t} + K_2 e^{-j\omega t} \quad (6)$$

where K_1 and K_2 are arbitrary constants. Its discrete form can be expressed as

$$x(n\Delta T) = K_1 e^{j\omega n\Delta T} + K_2 e^{-j\omega n\Delta T} \quad (7)$$

where $t=n\Delta T$, $n=1, 2, 3,\ldots$, and ΔT denotes the sampling time spacing. Let $d_1=e^{j\omega\Delta T}$ and $d_2=e^{-j\omega\Delta T}$, respectively, then Eq. (7) becomes

$$x[n] = K_1(d_1)^n + K_2(d_2)^n \quad (8)$$

and its characteristic equation can be expressed as

$$H(D) = (D-d_1)(D-d_2) \quad (9)$$

where the operator notation D denotes a discrete-time delay, e.g. $Dx[n]=x[n-1]$. The discrete time signal $x[n]$ satisfies a second-order difference equation $H(D)x[n]=0$, *i.e.*

$$x[n] - 2\cos(\omega\Delta T)x[n-1] + x[n-2] = 0 \quad (10)$$

In practical applications, an individual component of interest is usually contaminated with noise and other sinusoids. Therefore, Eq. (10) is modified to become,

$$x[n] - 2\cos(\omega\Delta T)x[n-1] + x[n-2] = \epsilon[n] \quad (11)$$

This equation is identical with the structural equation of the angular-velocity Vold–Kalman filter, which was introduced by Vold et al. in 1993 [26]. Vold–Kalman filter (VKF) is a powerful time-varying band-pass filter, which has several important characteristics. Firstly, the center frequency and bandwidth of filter can