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Ultrasonic NDE of thin Composite plate Based on an enhanced Wigner-Ville distribution

Gaohui WU, Jun SU, Dezhi ZHU, Huasong GOU, Wulan SHENG, Yan LI
School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang, P.O. Box 3023, No. 2 Yikuang Street, Harbin Institute of Technology, Harbin 150080, P. R. China
Tel: +86-451-86402373-4050, Fax: +86-451-86412164
Email: wugh@hit.edu.cn, susocjunsu@163.com

Abstract

Due to the inherent inhomogeneous and anisotropy nature of the composite material, Ultrasonic waves suffer high acoustic attenuation and scattering effect, thus making data interpretation difficult. Especially for thin composite plate, echoes from the internal delamination interfere with surface echoes. In the present work, an enhanced Wigner-Ville distribution (EWVD) is obtained based on the chirplet decomposition and signal elimination. Echoes that are useless and affecting representation of flaws are eliminated from Wigner-Ville distribution (WVD). Details of ultrasonic signal, containing information of damage level in composite plate, are shown obviously and can be well explained through the EWVD. Compared to traditional WVD, the EWVD is effective in flaw identification and quantification.

Key words: NDE, chirplet decomposition, composite, Wigner-Ville distribution

Introduction

Fiber reinforced metal matrix composite has been widely used in the field of aerospace，which is thin because of high specific strength and modulus for decreasing weight. Due to the non-homogenous nature of composite materials, new inspection techniques need to be developed for performing the analysis of NDE ultrasonic signals that can be highly complex[1]. For thin composite plate, echoes backscattered from the front (F-echo) and back (B-echo) surface of specimen, mixed with other backscattered echoes of flaws and composite structure, often are overlapped, making the identification of flaws difficult. Consequently, a well-adapted kind of signal analysis is required to interpret the ultrasonic inspection signals. Wigner-Ville distribution (WVD) of ultrasonic signal has been used for the characterization of materials and localization of flaws [2]. However, due to the inability of reducing the cross-terms, useful information is always hiding from WVD. Therefore, it’s necessary to perform signal processing before applying WVD. Ultrasonic echoes have been successfully decomposed into a linear combination of chirplet components [3-4]. Each chirplet is a nonlinear function of a set of parameters, which lead to the characterization of materials.

In this study, backscattered ultrasonic signals from a thin composite plate through pulse-echo method are decomposed into a superposition of many chirplets, which offer desirable analytic solution for time-frequency (TF) representation. F-echo and B-echo are separated from ultrasonic signals successfully through the chirplet decomposition method. By the elimination of the F-echo, details containing information of flaws are clearly shown in the TF representation when an enhanced WVD (EWVD) is applied to the decomposed backscattered ultrasonic signals. Characteristic of Damage with different level can be readily extracted from the TF representation.

Signals decomposition and EWVD of separated ultrasonic signal

In pulse-echo ultrasonic testing the backscattered echo from a single reflector can be modeled as

$$f_{\Theta}(t)=\beta\exp(-\alpha_1(t-\tau)^2+i2\pi f_c(t-\tau)+i\phi+i\alpha_2(t-\tau)^2) \quad (1)$$

Where $\Theta=[\beta,\alpha_1,\alpha_2,\tau,f_c,\phi]$ denotes the parameter vector, α_1 is the bandwidth factor, α_2 is the chirp-rate, β is the amplitude, f_c is the center frequency, ϕ is the phase, and τ is the time-of-arrival of the ultrasonic echo[4]. Comprehensive discussions about chirplet function and physical explanation of these parameters can be found in reference [5]

Wigner-Ville distribution (WVD) of a single chirplet has a form

$$WVD_{f_{\Theta}}(t,f)=\frac{\beta^2}{\sqrt{2\pi\alpha_1}}\exp(-2\alpha_1(t-b)^2-2[\pi(f-f_c)-\alpha_2(t-b)]^2/\alpha_1) \quad (2)$$

Which can be thought of as a joint time-frequency energy density function, describing the signal's energy distribution in the joint time-frequency domain.

Backscattered ultrasonic signals can be decomposed into a linear combination of chirplet components through the successive parameter estimation technique [3], which is

$$s(t)=\sum_{j=1}^{N}f_{\Theta_j}(t) \quad (3)$$

Where $f_{\Theta_j}(t)$ is the chirplet model, Θ_j is the parameter vector of $f_{\Theta_j}(t)$, and N is the number of chirplet components. Then, the chirplet-based Wigner-Ville distribution of ultrasonic signal $s(t)$ can be expressed as follows:

$$WVD_s(t,f)=\sum_{j=1}^{N}WVD_{f_{\Theta_j}}(t,f) \quad (4)$$

In which the average of the cross term is equal to zero[6]. The chirplet that is useless or affecting flaw feature extraction can be eliminated from the WVD. Then an enhanced WVD (EWVD) is obtained

$$EWVD_s(t,f)=\sum_{j=1,\,j\neq k}^{N}WVD_{f_{\Theta_j}}(t,f) \quad (5)$$

Where k stands for the chirplet that will be eliminated. Therefore, useless information can be separated from backscattered signals and useful information can be extracted through EWVD based on chirplet decomposition.

Result and discussion

Decomposition of backscattered signals from thin composite plate

2D woven graphite fibers reinforced 2024 Aluminum composite plate with thickness of 2 mm was fabricated by squeeze infiltration, and was impacted by a bullet with a diameter, weight, and speed of 1.2 mm, 2.6 mg and 2.55 km/s, respectively. There are delaminations around the impact point. The level of damage is related to the distance from the impact point. Backscattered signals of three positions (table 1) were collected through pulse-echo method. A 5 MHz transducer (focused Panametrics V307-SU) with a beam width (BW) of 1.0 mm at the focus and a focal distance of 100 mm was used to receive signals, sampled at 40 MHz. It can be seen from figure 1(g) that F-echo and B-echo are overlapped, mixed with other backscattered signals from the internal structure or flaws of composite. Therefore, it's difficult to extract information of flaws.

Table 1. Backscattered ultrasonic signals of positions with different damage level

Sampling position	Distance from of the impact point (mm)	Damage level
A	5	severely damaged
B	8	lightly damaged
C	20	undamaged

Table 2. Parameters of chirplets decomposed from backscattered signal of position C

Decomposed Echoes	Bandwidth [MHz]^2	Chirp-rate [MHz]^2	Arrive-time [μs]	Center-frequency [MHz]	Phase [rad]	Amplitude
(a)	35.73	-7.87	0.44	2.59	0.40	1.00
(b)	2.53	-3.83	1.48	1.71	-1.50	0.31
(c)	39.44	-4.20	0.66	7.28	-1.73	0.42
(d)	5.65	36.67	1.01	0.59	-0.60	0.16
(e)	51.53	2.21	1.41	1.01	1.65	0.22
(f)	19.64	-58.59	1.79	1.41	-2.26	0.08

Chirplet decomposition method [4] was applied to the overlapped signal of the undamaged position (C in table 1), and successfully separated the F-echo and B-echo, as shown in figure 1. The estimated signal is composed of 6 chirplets. It's obviously that figure 1(a) is the F-echo, and figure 1(b) is the B-echo. The left chirplets (c), (d), (e) and (f) are other echoes which may be created by the structure or flaws within the composite. All the parameters of each chirplet are tabulated in table 2. The complex composite structure results in high attenuation of ultrasonic, which not only decreases the energy, but also lowers the center frequency of B-echo compared with F-echo.

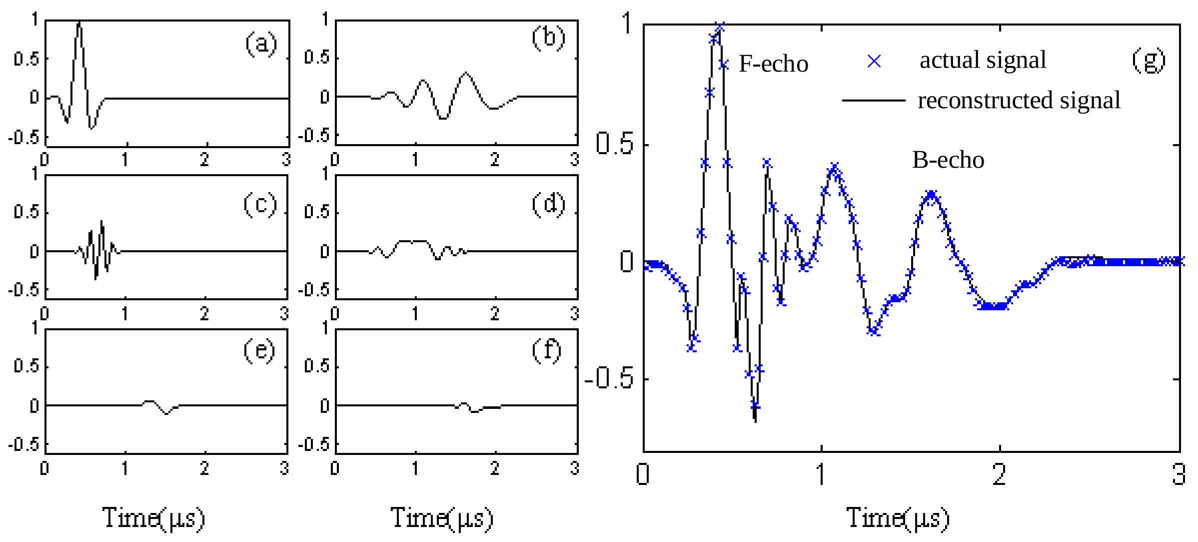

Figure 1. Chirplet decomposition of backscattered signal. (a)- (f) Chirplets decomposed from backscattered signal. (g) Actual (cross) and reconstructed signal (solid line).

Comparison of EWVD with different damage level

It can be seen from figure 3 (a) that F-echo dominates the energy of the signal. So the details of backscattered signal in WVD are not obvious, as can be seen from figure 2(a) and (b). It's well known that F-echo doesn't contain information of internal structure and flaws of material, and its shape is usually the same for specimens having the same roughness in pulse-echo method, such as C-Scan. Therefore, F-echo can be eliminated from WVD of backscattered signal [see figure 2(c)], since it has been separated through chirplet decomposition method. Compared with conventional WVD [see figure 2(a)], chirplet-based WVD can be well interpreted. By elimination of F-echo, EWVD shows more detailed information from flaws [see figure 2(c)], while it's impossible for the conventional WVD, as shown in figure 2(a).

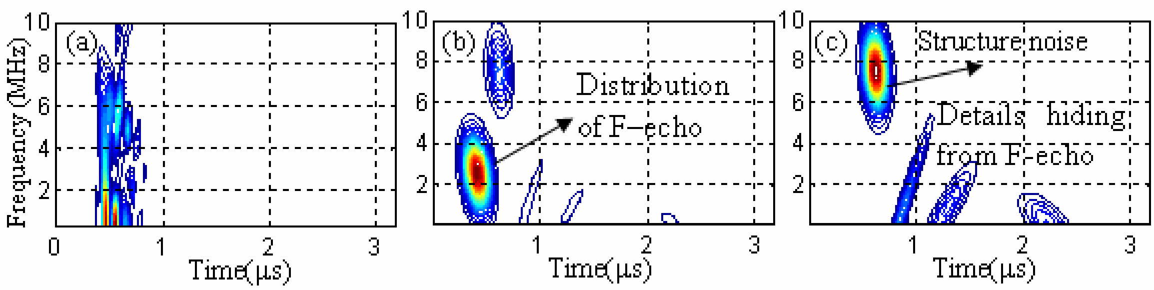

Figure 2. TF representation of ultrasonic signal at position A.
(a) Conventional WVD of backscattered signal. (b) WVD based on chirplet decomposition.
(c) EWVD of backscattered signal with elimination of F-echo.

EWVD of signals are shown in figure 3, in which F-echo has been eliminated. Figure 3(a), (b) and (c) are backscattered signals of A, B and C in table 1, respectively, and (d), (e), (f) are corresponding EWVD, respectively. Ultrasonic is reflected and scattered by flaws (mainly delaminations) at position A and B. It can be seen that main chirplets distribute loosely in EWVD at position A [see figure 3(d)]. Then become concentrated at position B [see figure 3(e)], while highly concentrated at position C, around the chirplet of B-echo in EWVD.

Because ultrasonic scattering becomes lower in lightly damaged and undamaged position (B and C), backscattered signal is mainly from B-echo. It also can be seen that there is nearly no chirplet of B-echo at position A, while chirplet of B-echo at position B is wide in time and narrow in frequency, and highly concentrated in time and frequency at position C. It shows that the feature of flaws is obvious and can be well interpreted from EWVD. As the signal composed of chiplets is analytic, it's readily to extract the level of damage and quantify the flaws.

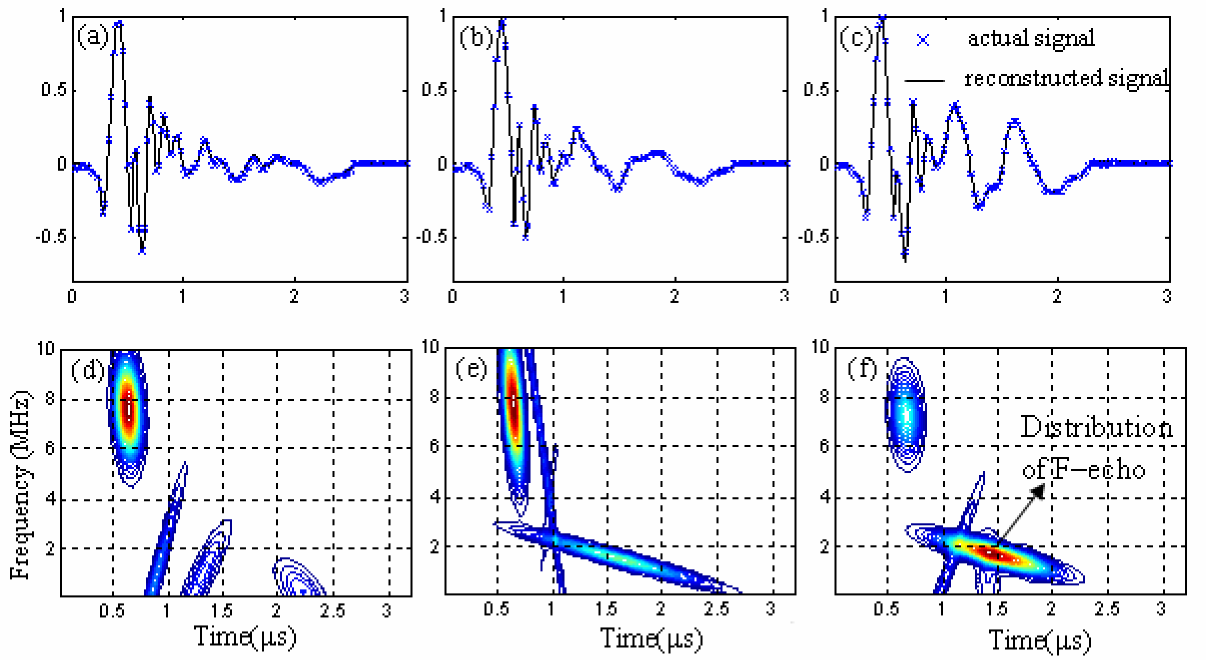

Figure 3. EWVD of signals of severely (A), lightly (B) damaged and undamaged (C) locations. (a), (b), (c) ultrasonic signals of A, B, C. (d), (e), (f) corresponding EWVD.

Conclusion

In this study, Wigner-Ville distribution has been successfully applied to the analysis and feature extraction of damage with different level, based on chirplet decomposition and F-echo elimination. By chirplet decomposition of backscattered signal, the F-echo and B-echo are separated from the backscattered echoes of thin composite plate, and F-echo is eliminated from WVD. Details of backscattered signal, which are reflection of internal state of composite materials, are shown obviously and can be well interpreted from EWVD. The chirplet parameters and EWVD can be used for identification and quantification of flaws.

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