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Hilbert Transform Pitfalls and Solutions for Ultrasonic NDE Applications

Erdal Oruklu*, Yufeng Lu** and Jafar Saniie*

* Department of Electrical and Computer Engineering
Illinois Institute of Technology
Chicago, Illinois 60616

** Department of Electrical and Computer Engineering
Bradley University
Peoria, Illinois 61625

Abstract— **Hilbert transform (HT) is a classical tool used to obtain complex analytical signal representation, which is useful for instantaneous frequency and envelop estimation of bandpass signals. However, noise has a significant adverse impact on the performance of HT. Furthermore, the narrowband signal condition in Bedrosian identity makes it problematic to analyze ultrasonic scattering signal using HT. In this investigation, two key issues related to Hilbert transform are addressed for enhanced instantaneous frequency (IF) estimation. First, in order to minimize the effect of the noise, ultrasonic signals are decomposed to multiple narrowbands and instantaneous frequencies within these bands are estimated. Second, a weighted estimated of IF based on envelop estimate of each narrowband is introduced. These methods are applied to various experimental ultrasonic data sets and utilized to examine microstructure scattering, effects of attenuation in large grained materials, and flaw detection in presence of high scattering noise. Simulation studies and experimental results support accuracy of the IF estimation. Enhanced IF estimation techniques provide tractable frequency estimation and makes it possible to quantify spectral shifts due to attenuation, scattering and dispersion effects.**

Keywords - Hilbert transform, instantaneous frequency, filter banks, ultrasonic NDE

I. INTRODUCTION

Different time-frequency (TF) analysis methods, such as short-time Fourier transform, Wigner-Ville distribution, wavelet transform, chirplet transform have been utilized to examine nonstationary signal often encountered in ultrasonic imaging applications[1-5]. However, it remains a very significant problem to obtain a general basis which is adaptive to nonstationary and interfering narrowband, broadband and dispersive echoes corrupted by noise.

Hilbert transform (HT) can be a viable alternative to display the time-frequency of nonstationary signals. It is a common tool to obtain an analytical representation of signal in terms of instantaneous frequency and amplitude. Instantaneous frequency and envelop of the analytical signal have been studied to analyze signals in communication, control and medical systems [6-9]. Recently, Hilbert spectrum has been used to examine the empirical decomposition of nonstationary and nonlinear signals [10-12]. This decomposition method has been explored in the applications of structural health monitoring, medical imaging, radar, speech, ultrasonic nondestructive evaluation, and climate variation analysis.

HT is an effective tool for estimating instantaneous frequency (IF) and envelop of signals. However, IF computation based on HT is highly sensitive to noise and also to interfering mutli-component signals such as ultrasonic scattering echoes. Furthermore, HT works well with narrowband signal but broadband signal may not satisfy the well-behaved analytic signal model based on Bedrosian theorem [13-14].

In this study, we analyze and model complex ultrasonic signals using HT, leading to an efficient characterization of materials with respect to frequency-dependent scattering, attenuation and dispersion effects. The challenges/pitfalls associated with the HT are presented, and then the remedies are introduced to overcome the limitations of the HT applied to ultrasonic signal processing.

This paper is organized as follows: Section II briefly reviews the HT and its limitations in ultrasonic signal analysis and presents the groundwork to overcome these limitations. Section III discusses the experimental study of ultrasonic signals using HT.

II. HT PITFALLS IN ULTRASONIC SIGNAL ANLAYSIS

To investigate the Hilbert transform pitfalls for ultrasonic NDE applications, it is gainful to analyze ultrasonic chirp echoes, a type of signal often encountered in ultrasonic backscattered signal accounting for narrowband, broadband, and dispersive echoes. An ultrasonic chirp echo can be modeled as [15-16]:

$$f_\Theta(t)=\beta\exp\left(-\alpha_1(t-\tau)^2\right)\cos\left(2\pi f_c(t-\tau)+\theta+\alpha_2(t-\tau)^2\right) \quad (1)$$

where $\Theta=[\tau \quad f_c \quad \beta \quad \alpha_1 \quad \alpha_2 \quad \theta]$ denotes the parameter vector, τ is the time-of-arrival, f_c is the center frequency, β is the amplitude, α_1 is the bandwidth factor, α_2 is the chirp-rate, and θ is the phase.

To analyze the time-frequency property of signal, $f_\Theta(t)$, Hilbert transform is applied to the signal, and the analytic signal, $Z_\Theta(t)$, can be defined as

$$Z_\Theta(t) = f_\Theta(t) + i\,H\left[f_\Theta(t)\right] \qquad (2)$$

where $H[\;]$ denotes the Hilbert transform. If the signal satisfies Bedrosian identity, which is the center frequency is larger the chirplet bandwidth [11], the analytic signal, $Z_\Theta(t)$ can be approximated with reasonable accuracy as

$$\begin{aligned} Z_\Theta(t) &\approx \beta \exp\left(-\alpha_1(t-\tau)^2 + i2\pi f_c(t-\tau) + i\theta + i\alpha_2(t-\tau)^2\right) \\ &= a(t)\, e^{i\int \omega(t)dt} \end{aligned} \qquad (3)$$

where $a(t) = \beta \exp\left(-\alpha_1(t-\tau)^2\right)$

$$\omega(t) = \frac{\partial\left(2\pi f_c(t-\tau) + \theta + \alpha_2(t-\tau)^2\right)}{\partial t} = 2\pi f_c + 2\alpha_2(t-\tau) \qquad (4)$$

Let $HT_{f_\Theta(t)}(t,\omega)$ denote the Hilbert time-frequency representation of the signal, $f_\Theta(t)$, which is

$$HT_{f_\Theta(t)}(t,\omega) = (a(t), \omega(t)) \qquad (5)$$

The maximum of $a(t)$ can be obtained by taking partial derivatives of the $a(t)$ with respect to t.

$$\begin{aligned} \frac{\partial a(t)}{\partial t} &= \beta(-2\alpha_1(t-\tau)) \exp\left(-\alpha_1(t-\tau)^2\right) \\ &= 0 \end{aligned} \qquad (6)$$

The solution of Equation (4) and (6) indicates that Hilbert time-frequency (TF) representation can be used to analyze ultrasonic chirp signal and reveal the most two critical parameters, i.e., time-of-arrival and center frequency.

$$t = \tau, \qquad \omega(\tau) = 2\pi f_c \qquad (7)$$

Similarly, in a multi-component ultrasonic signal, $s(t)$, which includes a linear expansion of chirp echoes, Hilbert TF representation can be obtained from its analytical signal $Z_s(t)$.

$$\begin{aligned} Z_s(t) &= s(t) + iH(s(t)) \\ &= \sum_{j=0}^{M-1} f_{\Theta_j}(t) + iH\left(\sum_{j=0}^{M-1} f_{\Theta_j}(t)\right) \\ &= \sum_{j=0}^{M-1} a_j(t)\, e^{i\int \omega_j(t)dt} \end{aligned} \qquad (8)$$

where $s(t) = \sum_{j=0}^{M-1} f_{\Theta_j}(t)$, which includes M chirp echoes. $a_j(t)$ denotes the amplitude, and $\omega_j(t)$ denotes the frequency of j th chirp echo.

To illustrate the advantages of Hilbert transform in ultrasonic signal processing, ultrasonic chirp echoes are simulated in Figure 1, where positive or negative chirp rate models the dispersive effect in ultrasonic testing of materials. It shows the estimated time-of-arrivals and center frequencies closely match the actual values used in simulating the signals.

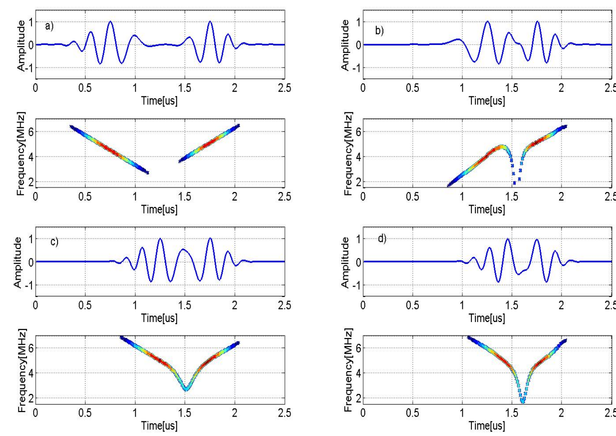

Figure 1. Hilbert TF representation of ultrasonic chirp echoes (row 2 : Hilbert TF representation of the ultrasonic Gaussian echoes in row 1; row 4 : Hilbert TF representation of the ultrasonic Gaussian echoes in row 3) .

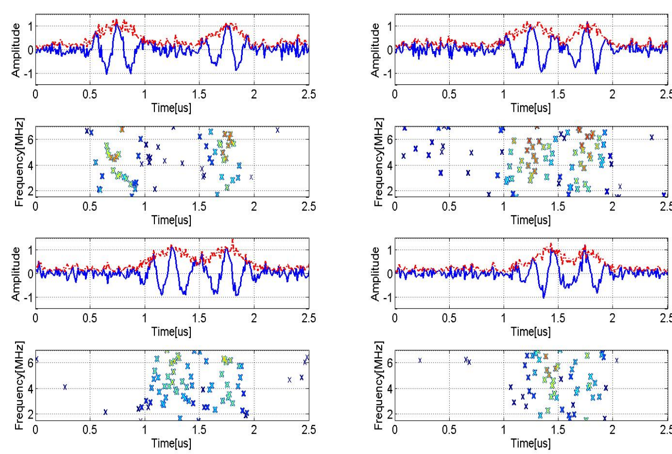

Figure 2. Hilbert TF representation of noisy ultrasonic chirp echoes (row 2 : Hilbert TF representation of the ultrasonic chirp echoes in row 1; row 4 : Hilbert TF representation of the noisy ultrasonic chirp echoes in row 3) .

It can be seen that HT is an effective tool for ultrasonic NDE applications. However, from equation (4), it can be seen that the instantaneous frequency (IF), $\omega(t)$, is a function of time, t, which indicates that any level of noise will deteriorate the accuracy of the HT-based time-frequency presentation. Furthermore, presence of noise becomes more dominant in HT time-frequency characterization of interfering multi-components signals such as ultrasonic scattering echoes. Figure 2 illustrates the pitfalls of the HT in ultrasonic signal processing. Noisy ultrasonic chirp echoes with different overlapping levels are simulated. The envelopes of the analytical signal are superimposed on the ultrasonic echoes. It can be seen that the Hilbert TF representation of the signals is heavily smeared by the noise.

To qualify the ultrasonic signal for Hilbert transform, we split the spectrum into multiple narrow bands using a filter bank structure. Consequently, the erroneous IF estimations due to broadband noise become discarded. Another key advantage of this approach is separation of echoes within different frequency bands. Furthermore, this decomposition operation also satisfies the Bedrosian identity by limiting the bandwidth of the signal. The ultrasonic signal shown in Figure 2 (row 1 and column 2) is used to demonstrate the performance of enhanced IF estimation using filter bank (see Figure 3). Compared with the deteriorated IF representation shown in Figure 2 (row 2 and column 2), the enhanced IF representation as shown in Figure 3 displays the IF of the signal more accurately.

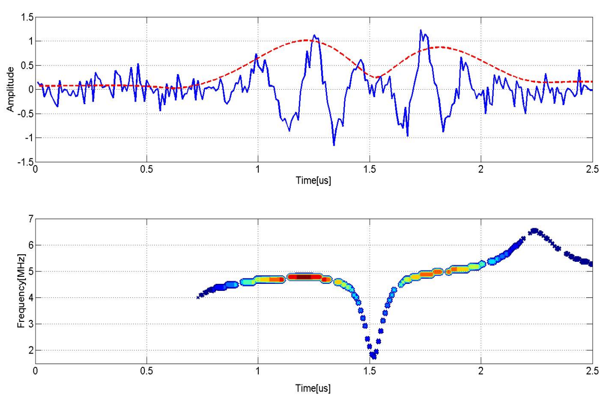

Figure 3. Noisy ultrasonic chirp echoes superimposed with the analytical ultrasonic signal using Hilbert transform and filter bank. Enhanced IF representation is the low figure and the enhanced estimated envelop is the dash line in the upper figure.

III. EXPERIMENTAL RESULTS

To evaluate the proposed remedies of Hilbert transform, an ultrasonic testing is conducted using a 5 MHz transducer and a sampling rate of 100 MHz to acquire ultrasonic backscattered signal from a steel block with a flat-bottom hole representing defects. The A-scan is shown in Figure 4 (top trace). Figure 4 also shows the IF estimation (see middle trace) which is heavily smeared by the noise (the circled areas in this trace highlights that the IF estimation contains valuable information of ultrasonic backscattered data which is not readily quantifiable in its present form). Therefore, a filter bank (refer to Figure 5) consist of 8 Gaussian narrowband filters are applied to the experimental signal. The overall band-limit effect of the filter bank is

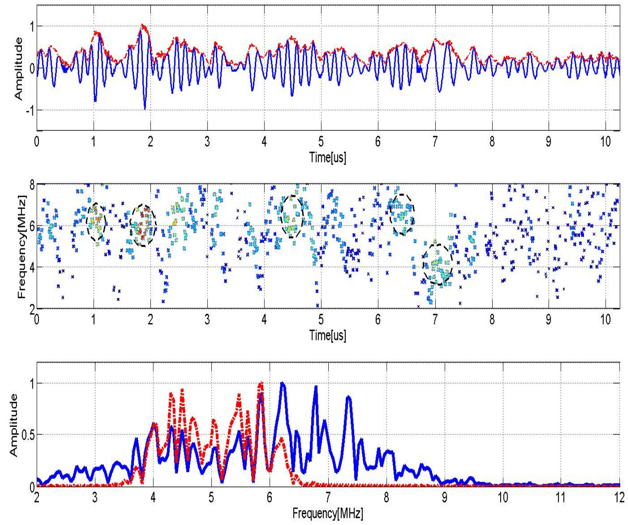

Figure 4. Ultrasonic experimental data with the estimated envelop (top trace), IF estimation (middle trace) and power spectrum of the signal (bottom trace in color blue) and the Gaussian bandpass spectrum (bottom trace in color red).

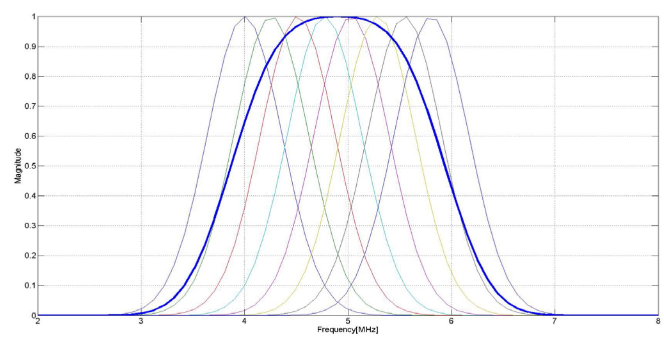

Figure 5. Filter bank of the proposed Hilbert solution. Heavy blue line shows the equivalent bandwidth that is covered by all narrowband filters used in the filter bank.

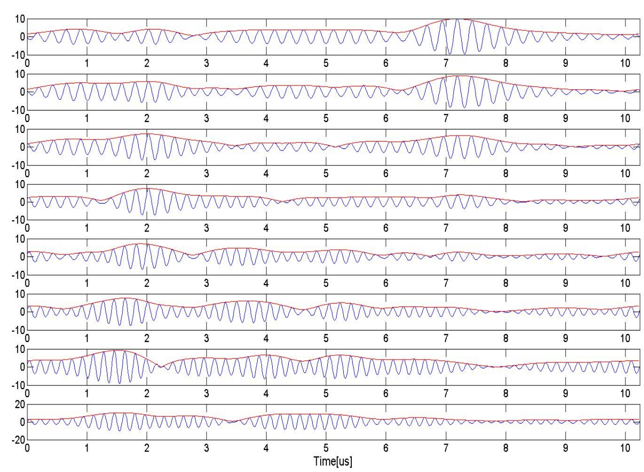

Figure 6. Filter bank outputs of ultrasonic experimental signals.

illustrated in Figure 4 (bottom trace depicted in red color). The outputs from the filter bank are shown in Figure 6. Furthermore, a denoised reconstructed signal is obtained by summing the filter bank outputs (see Figure 7 second trace from the top). The noise in the reconstructed signal has been greatly reduced and, consequently, the spectral shifts due to attenuation, scattering and dispersion effects are clearly visible in the enhanced IF representation of the signal (see Figure 7, third trace from the top). Moreover, it confirms that the target echo exhibits a lower center frequency compared to scattering echoes due to the effect of frequency-dependent attenuation [17]. Figure 7 (bottom trace) also shows an improved IF estimate (an overly smoothed result) using the weighted (envelope of each bandpass filter output is used as a weighting function, see Figure 6) sum of IF estimates corresponding to each filter within the filter bank.

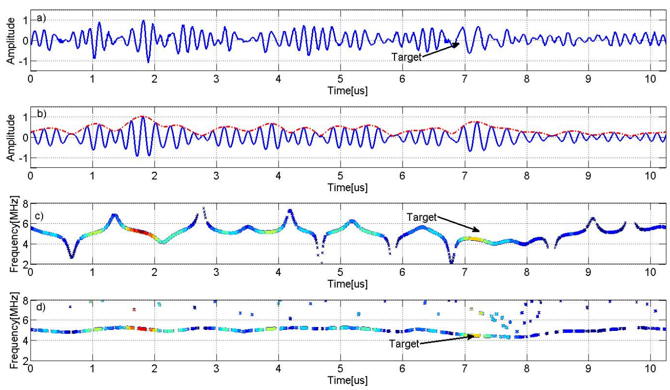

Figure 7. Ultrasonic experimental data (top trace), bandpassed signal and envelop (2nd trace from the top), the enhanced IF estimate using the bandpassed signal (3rd trace from the top); and the smoothed IF estimate (bottom trace).

IV. Conclusion

HT can be very effective for frequency analysis in ultrasonic signal analysis. However, it may result in misinterpretation of the frequency content of echo signals if not used correctly. In this paper, filter bank concept has been introduced to increase the robustness of the HT method by reducing its sensitivity to noise and by ensuring true analytic signal representations with the narrowband decomposition. Simulation studies and experimental results support accuracy of the IF estimation. Enhanced IF estimates provide tractable frequency information that can be correlated to frequency-shift due to attenuation, scattering and dispersion effects.

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