10.1109/ULTSYM.2009.0493

Applications of Time-Frequency Distributions for Ultrasonic Flaw Detection

Erdal Oruklu, Semih Aslan, and Jafar Saniie
Department of Electrical and Computer Engineering
Illinois Institute of Technology
Chicago, Illinois, 60616

Abstract— **In this study, we have examined time-frequency distributions Gabor transform, Wigner-Ville distribution, Choi-Williams distribution and Wavelet transform for improved flaw detection performance in ultrasonic nondestructive testing applications. A new methodology is presented with respect each T/F distribution methods, with necessary steps to achieve maximum flaw echo visibility enhancement. This methodology describes i) mapping ultrasonic signal to T/F domain, ii) projection from T/F representation back to time domain, iii) interpretation of the signal using order statistics. These steps include choosing the optimal time and frequency window sizes (based on Heisenberg principle), and the appropriate post-processing detection method to minimize the effect of null-observations. To demonstrate the validity of the methods, we discuss and draw an analogy between T/F distributions and the conventional Split-Spectrum Processing flaw detection method. The analytical and experimental studies verify the feasibility of the T/F techniques for NDE applications.**

Keywords-Flaw detection, NDT, Time/Frequency distribution, Gabor Transform, Wavelet Transform, WignerVille Distribution)

I. INTRODUCTION

In ultrasonic NDE applications such as detecting fatigue cracks, void and delamination in large grain materials, defect echoes are often concealed by clutter resulting from grain scattering. In the past, studies have been performed to improve flaw visibility based on frequency diversity [1]. In Rayleigh region where the echo wavelength is larger than the grain size, the scattering is highly dependent on the frequency of interrogation. Consequently, when testing the materials using a broadband transducer, there is an upward shift in the expected frequency of scattered echoes. On the contrary, the echoes from defects represent a downward shift with respect to transducer frequency due to the effect of frequency-dependent attenuation [1]. This paradox in frequency shift is advantageous for locating the defect. Therefore, methods that meet the criteria for improved flaw detection are time-frequency (T/F) distributions. The backscattered signal information in ultrasonic nondestructive testing is non-stationary due to frequency dependent scattering, attenuation and dispersion. The standard spectral analysis cannot determine the time of arrival of different frequency components in the signal. Joint T/F representations of such signals are more revealing. Therefore, the objective of this study is to analyze T/F distributions, Gabor Transform (GT), Wigner-Ville Distribution (WVD), Choi-Williams (CW) distribution and Wavelet Transform (WT) for optimal ultrasonic flaw detection. We propose a new design methodology based on order statistics and compare the ultrasonic detection performance against the conventional Split-Spectrum processing (SSP) algorithm.

In Section II, we briefly discuss the T/F methods employed in this study. Split Spectrum Processing and order statistics methods for ultrasonic flaw detection is described in Section III. A new T/F mapping, projection and interpretation technique for flaw detection applications is presented in Section IV. Finally, experimental results are shown and discussed in Section V.

II. TIME-FREQUENCY DISTRIBUTIONS

T/F methods GT, WVD, and CW are members of Cohen's [2] generalized T/F representation. Among these methods, only WVD can achieve optimal T/F concentration and represent a single Gaussian ultrasonic backscattered echo due to both time and frequency marginals satisfied. However, a major drawback for WVD is the presence of cross-terms for signals containing multiple echoes. Furthermore, WVD is very sensitive to noise. For T/F representations, there is a tradeoff between the cross-terms elimination and the marginal properties. For example, Pseudo Wigner-Ville distribution uses windowing to eliminate cross-terms; however it loses marginal properties. Choi-Williams [2] can attenuate to some extent the cross-terms without sacrificing the marginal properties with reduced interference distribution. On the other hand, Gabor transform (GT) is immune to cross-terms. The biggest limitation of GT (which is simply short time Fourier transform (STFT) with the Gaussian window) is the comparison between the time and frequency resolution of the analysis due to the Heisenberg principle [2]. Good time resolution implies a small time window, which results in a poor frequency resolution and vice versa. The optimal concentration of GT is obtained when GT's window parameter matches the duration parameter of the ultrasonic echo [3]. While the STFT compromise between time and frequency information can be useful, the drawback is that once you choose a particular size for the time window, that window is the same for all frequencies.

Wavelet transform which does not generate any cross-terms, is a time-scale distribution and uses a flexible window for analyzing different frequency components in a signal. Unlike GT and STFT, in this method of constant-Q analysis using (WT), the shape of the window changes with frequency, keeping the relative bandwidth constant. It is desirable in certain applications to have better time resolution at higher frequencies than at lower frequencies.

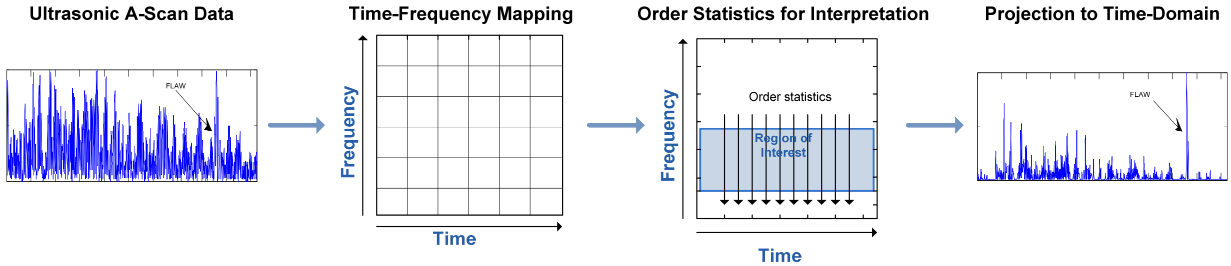

Figure 1. Proposed flaw detection methodology based on time-frequency distributions.

III. Split Spectrum Processing and Flaw Detection

In ultrasonic imaging of materials, an effective method of obtaining frequency diverse information is through split spectrum processing (SSP) of the broadband echoes [1,4]. SSP method entails transmitting a broadband signal into the media and partitioning the received signal into several narrowband channels. The algorithm can be described as follows: The first step involves fast Fourier transform (FFT) which gives the frequency spectrum of the received echo signal. In the second step, several filters split the signal spectrum into different narrow frequency bands. Next step, inverse FFT gives the time domain signal of each individual frequency band. Observations from each channel cover the bandwidth of the frequency spectrum of the transducer and each observation contributes to signal-to-noise improvement. Therefore, at any given time, the outputs of bandpass filters can be represented as a random feature vector that contains information related to flaw and grain echoes. The signals from each individual frequency band (SSP channel) are passed into a post-detection processor. This processor can employ different techniques such as *minimization, median and maximization* [1]. These methods all fall under the category of order statistic (OS) filters that have been readily developed in the statistics field, and have found applications in radar, sonar and image processing. The mathematical expressions of these techniques are given as the following:

Median detector	$\phi_{med}(n) = median[\lvert z_j(n)\rvert, j = 1,2,\ldots,k]$
Minimum detector	$\phi_{min}(n) = \min[\lvert z_j(n)\rvert, j = 1,2,\ldots k]$
Maximum detector	$\phi_{max}(n) = \max[\lvert z_j(n)\rvert, j = 1,2,\ldots k]$

where z_j is the SSP output on channel j, and k is the total number of the SSP channels. Order statistics, minimization in particular; has shown to be more effective for the situation in which the flaw signal is present in all of the channels, although, this is not always the case in practice. The flaw signal may not be present in some frequency bands due to sensitivity to frequency shifts and/or significant attenuation caused by the grains of the material. Under these circumstances, a more robust operator is needed and minimization may not perform satisfactorily. Important issues in SSP are the number of observations, correlation between observations, and statistical information in each observation.

IV. Proposed Methodology for T/F Distributions

A. Flaw Detection with GT, CW, and WVD

In this work, a new T/F design approach is presented for ultrasonic flaw detection applications. This approach is influenced by the subband decomposition and post-processing methods first introduced with the SSP algorithm [1]. Due to unique spreading characteristics of each T/F distribution, localization of flaw echoes can be achieved successfully. Figure 1 shows the design flow and the necessary steps for improved flaw detection.

1. Initial step is the selection of T/F method and mapping ultrasonic A-scan data onto T/F coordinates. The particular method chosen plays an important role in spreading the non-stationary signal information into time and frequency axis and determining the resolution of the windows. As discussed in Section II, GT, WVD and CW provide diverse 2D mappings of the ultrasonic echoes. We will analyze their properties for flaw detection in the next section.
2. The second step is projection of T/F representation back to time domain. For this operation, a region of interest (ROI) is selected covering a subset of the frequency components based on the frequency characteristics of the flaw and clutter echoes. If this a-priori information is not available, a wider frequency spectrum range is used which may cause a significant impact on the performance of the post-processing operation for flaw detection.
3. Final step is post-processing using order statistics; minimization, median and maximization. Order statistics interprets the frequency content at each sample point (time) and successfully highlights the presence of flaw echo. Results indicate that minimization performs superior when ROI is properly selected. For median and maximization, ROI has less impact in the final outcome for flaw detection.

B. Flaw Detection With Wavelet Transform

In earlier work [5], we have explored techniques to benefit from both temporal and spectral properties of wavelet transform (WT) for enhancing flaw echo visibility. In particular, the compactness properties of the WT allow a region of interest to be determined in time-frequency representation which is essential for flaw detection. 2D moving windows across several wavelet scales within this region of interest are utilized to reconstruct a family of signals that bear dominant information from the flaw echo. Order statistics processing of this family of reconstructed signals

TABLE I. FLAW DETECTION PERFORMANCE COMPARISON BETWEEN T/F REPRESENTATIONS

Input Data	Input FCR (dB)	Time-Frequency Distribution Methods										Split-Spectrum Processing (FFT)
		Gabor			Wigner-Ville			Choi-Williams			Wavelet Coiflet (1,5)	
		MIN	*MED*	*MAX*	*MIN*	*MED*	*MAX*	*MIN*	*MED*	*MAX*	*MIN*	*MIN*
A-SCAN #1	-0.14	10.8	2.9	-2.9	3.1	4.0	5.4	10.5	-1.1	-6.0	6.92	10.75
A-SCAN #2	0.8	11.5	2.3	1.3	9.5	-5.1	-9.3	1.2	3.3	2.8	7.04	7.21
A-SCAN #3	-2.1	14.6	7.6	2.2	15.3	0.5	-4.5	2.4	3.8	5.7	8.78	14.82
A-SCAN #4	-3.5	9.1	4.3	-0.6	13.9	-2.6	-9.0	1.3	2.6	2.8	10.27	10.17
A-SCAN #5	-3.7	17.0	3.7	2.0	3.7	1.6	-0.2	1.2	2.9	4.2	13.47	12.33
A-SCAN #6	-4.2	19.5	3.1	-1.7	2.3	0.4	-3.3	-2.8	-1.1	0.4	12.5	12.78
AVERAGE	-2.1	**13.7**	**4.0**	**0.0**	**8.0**	**-0.2**	**-3.5**	**2.3**	**1.7**	**1.7**	**9.83**	**11.54**

TABLE II. PROPERTIES OF T/F REPRESENTATIONS FOR ULTRASONIC FLAW DETECTION

	Gabor Transform	Choi-Williams Distribution	Wigner-Ville Distribution	Wavelets
Strength	• Best minimization performance overall. • No cross terms. • Window can be narrowed to get increased time resolution or vice versa. • Easy to implement.	• Good T/F resolution can be achieved. • Marginals are satisfied. • Reduced interference distribution.	• FCR improvement possible with minimization. • Good T/F resolution can be achieved. • Marginals are satisfied.	• FCR improvement is good, dependent on wavelet kernel. • Very flexible. • Good time resolution at high frequencies. • Variety of wavelet kernels can be used for characterizing ultrasonic echoes.
Weakness	• Time-frequency resolution limited by the Heisenberg principle (Localization is limited). • Orders statistics median and maximization do not work as well as minimization.	• Spreading effect for dominant echoes in frquency domain. • Order statistics, minimization in particular; works poorly.	• Cross-terms. • High sensitivity to noise.	• Coarse time resolution at low frequencies.

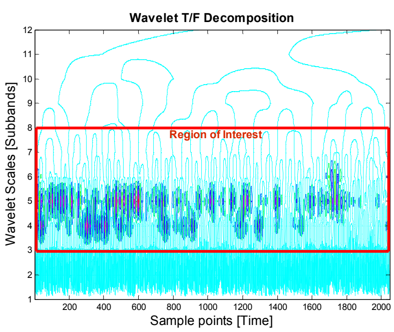

Figure 2. Wavelet scales and ultrasonic A-scan data

results in significant flaw-to-clutter ratio enhancement. An important question is determining the frequency bands (scales) to be used for post-processing

Since the clutter echo spectrum is shifted towards higher frequencies, the flaw echo is expected to be the dominant information in lower frequencies. Wavelet domain scales (for experimental data with 2048 data points and 11 wavelet scales) in Figure 2 confirm that the lowest scales (high frequencies) are mostly clutter information, whereas the higher scales represent the low-passed version of the ultrasonic data. Therefore, the desired frequency bands lie in the center scales. The inspection of Figure 2 confirms that the intermediate scales 3 to 6 contain dominating flaw information. Therefore, intermediate scales are a desirable choice for post processing and should be part of the Region of Interest (ROI). It is important to point out that the low-rank order statistics method including minimization is very effective if, and only if, there is no null-observation in the selected scales. Therefore, the following steps are critical for flaw detection applications that incorporate WT decomposition:

1. Choose an appropriate wavelet kernel (compactness is important). If the wavelet kernel shape is similar to the ultrasonic flaw echo, then the flaw echo is going to be dominant in a particular scale.
2. Identify the wavelet scales that carry flaw echo spectrum information.
3. Determine how many windows (i.e., bandpass filters in the SSP method) are to be utilized for signal reconstruction.
4. Perform inverse WT for each window.
5. The resulting ensemble of observations feeds the order statistics processor. In the reconstructed signal, the flaw echo is made more visible due to the vulnerability of clutter echoes to changing of wavelet scales.

V. EXPERIMENTAL RESULTS

For performance evaluation, experimental measurements from steel blocks (type 1018 with different grain sizes including single or multiple defects) are acquired using an ultrasonic pulse-echo system with 5 MHz broadband transducers. The comparative results show the strengths and deficiencies of each method. T/F distributions are particularly effective, matching and exceeding SSP performance when the signal is analyzed with a priori information about the transducer bandwidth and the expected frequency-shift due to scattering and attenuation. Figures 3 to 6 illustrate this phenomenon. In Figure 3, GT, WVD and CW T/F representations of experimental ultrasonic data are shown with the ROI selected to be between 2 MHz and 5 MHz, based on expected frequency downshift behavior of flaw echoes. It can be seen that the flaw echo is highly localized and separated from other dominant echoes in the frequency spectrum. Corresponding flaw detection results using order statistics are presented in Figures 4 - 6 from (a) to (d). In all three methods, minimization works very well with significant flaw-to-clutter ratio improvement. Median

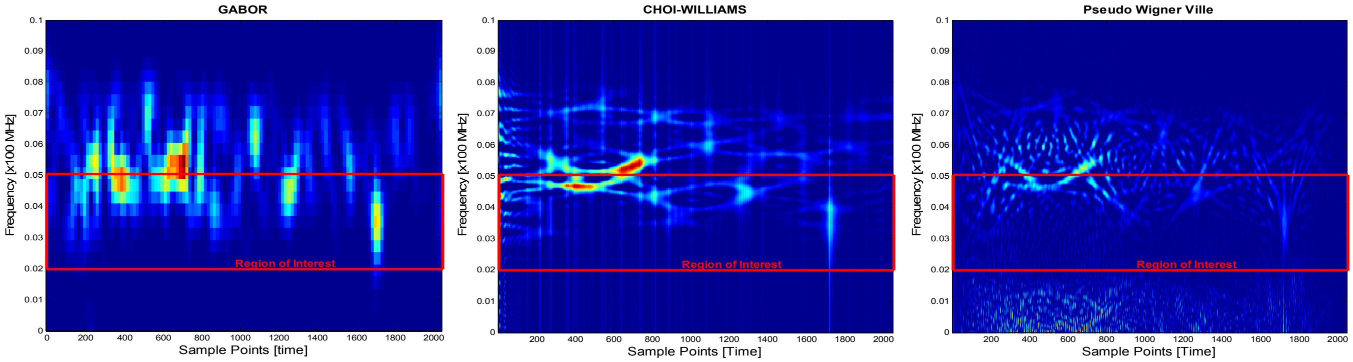

Figure 3. Time Frequency Representation of Ultrasonic Signals using GT, CW and WVD.

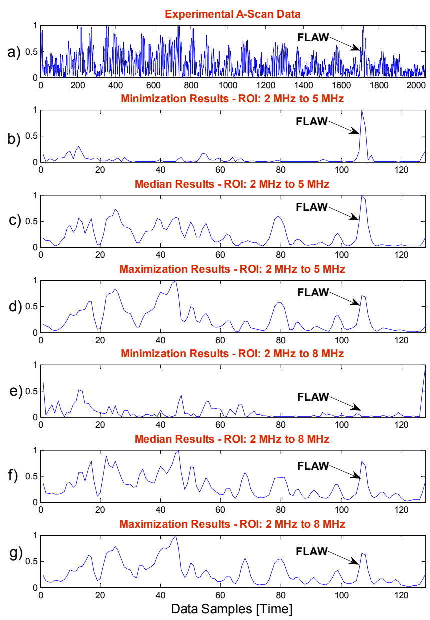

Figure 4. Gabor Transform flaw detection.

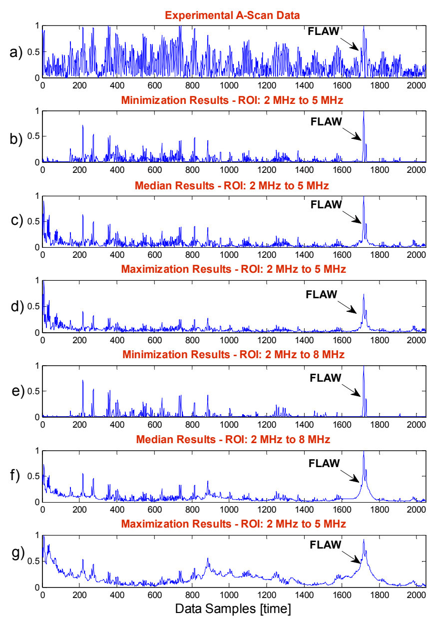

Figure 5. Choi Williams Distribution flaw detection.

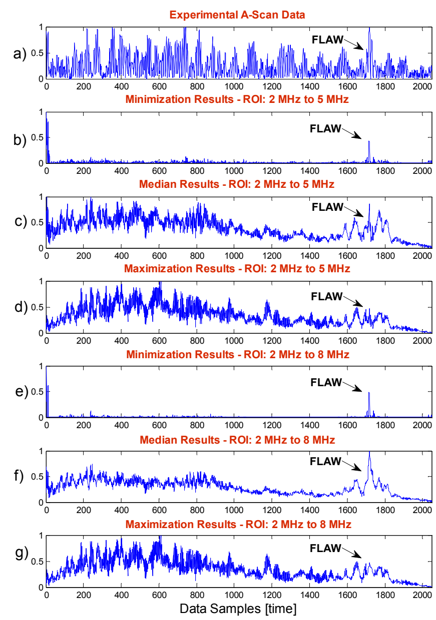

Figure 6. Wigner Ville Distribution flaw detection.

and maximization do not perform as good in GT and WVD due to insufficient window resolution and spreading. For the flaw detection results seen in Figures 4 - 6 from (e) to (g) , the ROI is expanded to double the size ranging from 2 MHz to 8 MHz spectrum coverage. As expected, minimization fares poorly due to null observations introduced especially in the GT case, while median and maximization behaves more robustly with slight deterioration in their performance.

Table I lists the analysis of several ultrasonic experimental signals and the FCR improvement results using the proposed T/F techniques and the conventional SSP method using order statistics. For performance analysis, flaw-to-clutter ratio (FCR) is calculated by finding the maximum flaw echo (reflection from hole location) amplitude in the reconstructed signal. This value is compared with the largest amplitude of clutter echoes.

$$FCR = 20 * \log_{10}(F/C)$$

where F is the maximum flaw echo amplitude and C is the maximum clutter echo amplitude. It can be seen that GT has the best FCR improvement performance since there are no cross-terms and spreading noise compared to WVD and CW. Table II summarizes the properties of the T/F methods for ultrasonic flaw detection applications and highlights their advantages and shortcomings.

VI. Conclusion and Summary

In this work, we have developed and analyzed methods for improved ultrasonic flaw detection using T/F distributions. T/F representation exploits the frequency sensitivity of grain scattering and focuses on the T/F region where the flaw-to-clutter ratio is maximal. The analytical and experimental studies verify the feasibility of the T/F techniques for NDE applications.

References

[1] J. Saniie, D. T. Nagle, and K. D. Donohue, "Analysis of order statistic filters applied to ultrasonic flaw detection using split-spectrum processing", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control,* vol. 38, no. 2, pp. 133-140, March 1991.

[2] Leon Kohen, Time Frequency Analysis: Theory and Applications, Prentice Hall PTR, 1994.

[3] M.A. Malik and J. Saniie, "Performance comparison of time-frequency distributions for ultrasonic nondestructive testing", *Proceedings of IEEE Symposium on Ultrasonics*, vol. 1, pp. 701-704, November 1996.

[4] V. Newhouse, N. Bilgutay, J. Saniie, and E. Furgason, “Flaw-to-grain echo enhancement by split-spectrum processing,” *Ultrasonics*, vol. 20, pp. 59–68, March 1982.

[5] E. Oruklu and J. Saniie. “Ultrasonic target detection using discrete wavelet transform for NDE applications,” in *Proceedings of IEEE Symposium on Ultrasonics*, vol. 2, pp. 1054–1057, August 2004.