HIGH SPEED DESIGN AND PERFORMANCE EVALUATION OF FREQUENCY-DIVERSE ORTHOGONAL TRANSFORMS FOR ULTRASONIC IMAGING APPLICATIONS

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Abstract - Ultrasonic flaw detection in the presence of high scattering grain noise is a significant problem in the non-destructive evaluation (NDE) of materials. In this work, signal processing methods for ultrasonic flaw detection that incorporate discrete cosine transform (DCT), and discrete Walsh-Hadamard transform (WHT) will be presented. These are orthogonal transforms that are suitable candidates for integration in a system-on-chip (SoC) architecture design where computational complexity may be critical. The flaw detection systems for DCT and WHT are implemented in a way that is similar to the conventional split spectrum processing (SSP) methods. Experimental data results demonstrate that these methods are as effective as the SSP method for flaw detection in presence of high scattering grain noise. Efficient designs to optimize the hardware architectures for DCT and WHT based flaw detection applications are also discussed.

I. INTRODUCTION

Split Spectrum processing (SSP) is one of the common ultrasonic NDE techniques that is used to detect anomalies/flaws within the microstructure of the material [1]. The major challenge for building real-time NDE applications comes from hardware realization of SSP. Sampling rates can reach 100MHz or more depending on the transducer used and the number of samples required by the transform algorithm in SSP. Any application specific integrated circuit (ASIC) or field programmable gate array (FPGA) solution should be able to accommodate fast transform implementations and large data storage.

SSP entails dividing the spectrum into subbands using bandpass filters and applying detection algorithms to improve flaw-to-clutter ratio and flaw visibility. Digital bandpass filtering requires several forward and inverse fast Fourier transforms (FFT). The FFT is computationally intense, and for N data points it requires $2N\log_2 N$ multiplications and $2N\log_2 N$ additions. DCT offers optimal energy compaction and is related to FFT. The implementation of DCT needs significantly less logic compared to FFT. DCT of N data points based on Chen's algorithm [2] requires $N((3/4)\log_2 N-1)+3$ multiplications and $N((7/4)\log_2 N-2)+3$ additions. Similarly WHT offers subband decomposition and is especially simple to implement since the WHT matrix includes only +1's and -1's. Therefore, WHT requires no multiplications and needs far less logic. An ultrasonic flaw detection architecture that is suitable for VLSI implementation can be developed using these transforms. This architecture can be the basis of the foundation for a system-on-a-chip (SoC) application. Today the trend is for compact and small devices, and SoC solutions are tremendously beneficial for this purpose.

II. FREQUENCY-DIVERSE SIGNAL DECOMPOSITION

An effective method of obtaining frequency diverse information is through split spectrum processing of the broadband echoes backscattered from the materials. Since the microstructure of the test material consists of randomly distributed reflectors and grains, the detected echoes exhibit randomness in amplitude and they are sensitive to shifts in the transmitted frequency. In contrast, flaws are often larger in size and are less vulnerable to variation in the transmitted frequency. Traditionally FFT has been used in split spectrum processing but other transforms can also achieve frequency diversity. This section describes what's involved in these methods. Similarities and differences when using DCT or WHT will be presented.

A. FFT based split spectrum processing

In general, flaw echoes exhibit different scattering distributions as a function of frequency when compared with grain scattering. 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. FFT based split spectrum processing procedure has five steps. See Figure 1.

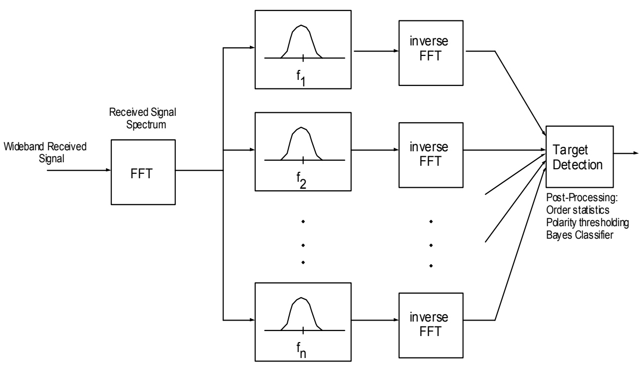

Figure 1 – Split spectrum processing

The first step is data acquisition. In the second step, FFT gives the frequency spectrum of the received echo signal. In the third step, several filters split the spectrum into different frequency bands. Different split spectrums are produced by passing through overlapping Gaussian filters with different center frequencies. With the next step, inverse FFT gives the time domain signal of each individual frequency band. In the last step, the signals from each individual frequency band are passed into a *processor* and output is generated. This processor can employ different techniques such as averaging or minimization [3],[4].

B. Discrete Cosine Transform

DCT can be used to replace FFT steps in SSP implementation. It has optimal performance in terms of energy compaction capability, the transform is real and many fast DCT algorithms with efficient hardware and software implementations have been proposed. The DCT has found wide applications in image/video processing and other fields. It has become the heart of many international standards such as JPEG, H.26x, and the MPEG family.

The 1D discrete cosine transform (1D DCT) X(k) of a sequence x(n) of length N is defined as

$$X(k) = \alpha(k)\sum_{n=0}^{N-1} x(n)\cos\left(\frac{\pi(2n+1)k}{2N}\right) \quad \text{for } k = 0,1,\ldots,N-1 \tag{1}$$

The inverse DCT is defined as

$$x(n) = \sum_{k=0}^{N-1} \alpha(k)X(k)\cos\left(\frac{\pi(2n+1)k}{2N}\right) \quad \text{for } k = 0,1,\ldots,N-1 \tag{2}$$

Where in both equations α(k) is defined as

$$\alpha(k) = \begin{cases} \sqrt{\frac{1}{N}}, & for \quad k = 0 \\ \sqrt{\frac{2}{N}}, & for \quad k = 1,2,\ldots,N-1 \end{cases}$$

C. Walsh-Hadamard Transform

Walsh-Hadamard transform is often used in speech and image processing. It is an orthogonal transform, with only additions and subtractions required and it is faster than sinusoidal-like transforms. It has a fast algorithm which has $Nlog_2N$ additions and subtractions for N-point input samples. The Hadamard transform can be interpreted as a decomposition of a signal by rectangular waveforms, whereas FFT decomposes a signal by sine-cosine waveforms. The number of zero crossings (divided by two) of the Hadamard basis sequences is known as the *sequency*, similar to frequency for sinusoidal signals. WHT is the sequency ordered Hadamard transform. This transform exhibits energy compaction property and has a fast Hadamard transform called FHT. WHT can be obtained from Hadamard matrix by multiplying it by a normalizing factor so that $HH^T=I$ instead of NI, and by reordering the rows in increasing sequency order. WHT for $N=2^m$ is given as

$$X(k) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x(n)(-1)^{\sum_{i=0}^{m-1} b_i(n)p_i(k)}, \quad \text{for } k = 0,1,\ldots,N-1 \tag{3}$$

$$x(n) = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} X(n)(-1)^{\sum_{i=0}^{m-1} b_i(n)p_i(k)} \quad \text{for } n = 0,1,\ldots,N-1 \tag{4}$$

where

$$p_0(k) = b_{m-1}(k) \tag{5}$$

$$p_j(k) = b_{m-j}(k) + b_{m-j-1}(k) \quad for \quad j = 1,2,\ldots m-1 \tag{6}$$

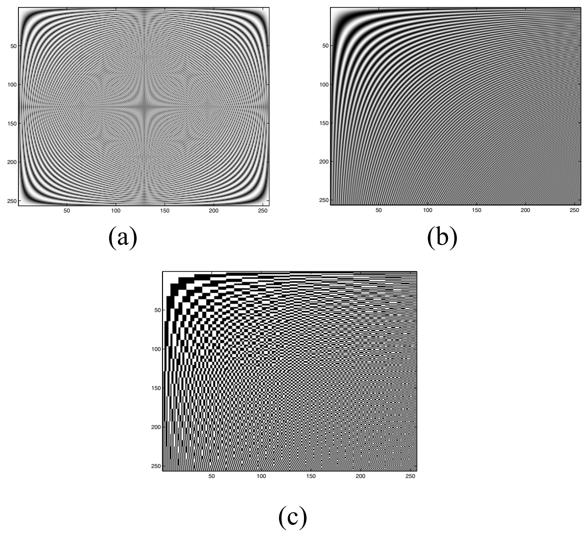

Figure 2: Transform kernel images.
(a) 256-point FFT (real) kernel, (b) 256-point DCT kernel, (c) 256-point WHT kernel

III. DCT AND WHT FOR FLAW DETECTION

The integration of discrete cosine transform and Walsh-Hadamard transform into split spectrum processing is very similar to classical SSP which uses FFT. The primary goal is to improve the visibility of the flaw and certain modifications are necessary to obtain this goal. The spectral properties of each transform are different: DCT does not have mirror-like spectrum as FFT, and WHT has information spread all across the spectrum. Figure 3 shows different transform domain signals for experimental ultrasonic data.

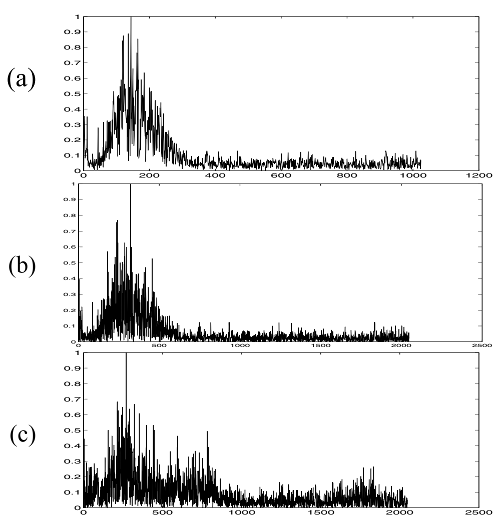

Figure 3. Ultrasonic data in transform domain (a) FFT domain signal, (b) DCT domain signal, (c) WHT domain signal

Bandpass filtering parameters are different for each transform. The bandwidth of the filters (Gaussian windows) in the filter-bank and the overlap between successive filters are not kept the same for different transforms. For an objective comparison, the number of the filters in the filterbank is always kept the same and equal to 8. Increasing the number of filters would improve the performance but it also means a more complex design. The parameter selection to optimize the detection process is critical since SSP technique is fairly sensitive to the frequency region used to obtain the narrowband signals and the performance of SSP is strongly influenced by the utilized spectral region. Overlapping Gaussian windows concentrate on the low-frequency section of the transform domain signals since high frequency components are more likely to carry grain noise information. This spectral region is configured for each transform separately.

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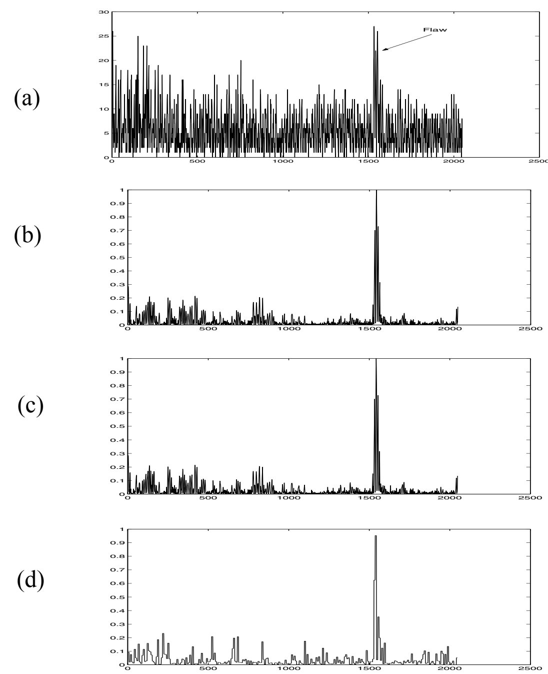


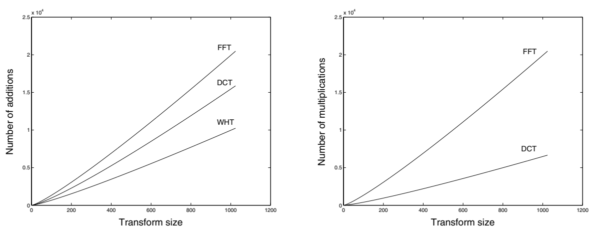
Figure 4. Comparison of different transform methods for flaw detection using experimental data: (a) Original ultrasonic data (b) FFT minimization, (c) DCT minimization, (d) WHT minimization

Figure 4 shows the flaw-detection results obtained using the proposed transforms for A-scan measurements. These A-scan measurements were conducted using steel blocks and a 0.5 inch transducer with 10 MHz frequency. Data were acquired with 100 MHz sampling rate. Original data has almost 0 dB flaw/clutter ratio. The FFT, DCT and

WHT based flaw detection algorithms enhances flaw/clutter ratio by approximately 12dB for this experimental data.

IV. Discussion

Our goal is to find an architecture with minimal hardware and low-power properties that can satisfy the high data throughput requirements of ultrasonic flaw detection algorithms. For this purpose, we examined fast orthogonal transforms with minimal hardware logic requirements that can perform as well as FFT based SSP for NDE applications. The orthogonal transforms examined in this work are faster to implement compared to the utilization of FFT and it is shown that their SSP performance closely matches to the performance of FFT based SSP. Figure 5 shows the algorithm complexity of these transforms. For large transform sizes, the computational margin between FFT and other transforms rises sharply.



(a) (b)

Figure 5. Algorithm complexity (a) number of additions, (b) number of multiplications

DCT can be implemented by using the binDCT method that does not require any multiplication operations [5]. The binDCT is an approximation algorithm for DCT that has fixed–point implementation. It uses Chen's factorization but replaces each plane rotation with lifting steps. DCT coefficients are approximated by dyadic values (rationals in the format of $n/2^m$, n and m integers). Multiplication by these coefficients requires only shift and add operations. An 8-bit DCT transform can be realized with binDCT using as low as 28 additions and no multiplications with minimal loss. (8-point FFT requires 48 multiplications and 48 additions). Considering the throughput requirements for ultrasonic NDE applications, the computational gain of using binDCT instead of FFT is significant. This implies small chip area (no dedicated floating point multiplier and no coefficients ROM necessary) and less power consumption (lower clock speeds can be used) for VLSI realizations. Figure 5 shows WHT has the lowest complexity compared to FFT and DCT algorithms. Fast WHT implementation has a sparse transform matrix with only 1, -1, 0 values. Distributed arithmetic (DA) techniques can be used in FPGAs to realize WHT based flaw detection algorithms. WHT is an efficient solution especially if hardware cost is the major drawback for the target application.

V. Summary

In this paper, we presented two orthogonal transforms for ultrasonic NDE applications. Both proposed methods achieve the suppression of grain echoes even when the flaw/clutter ratio is unity. The results indicate that DCT and WHT are viable substitutions to FFT for ultrasonic NDE applications. These transforms are good candidates for real-time hardware implementation of flaw-detection applications since they can substantially reduce the hardware logic requirements.

VI. References

1. V.L. Newhouse, E.S Ferguson, N. M. Bilgutay, and J. Saniie, "Flaw to grain echo enhancement" *Proc. of Ultrasound International Conference*, pp.152-157, 1979.
2. C. H. Smith, W. H. Chen and S.C. Fralick, "A Fast computational algorithm for DCT", *IEEE Trans. on Comms.*, pp. 1004-1009, September 1977.
3. 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, pp. 133-140, March 1991.
4. T. Wang, J. Saniie and X. Jin, "Performance Evaluation of Frequency-diverse Bayesian Ultrasonic Flaw Detection", *J. of Acoust. Soc. of Amer,* pp. 2034-2041, Apr. 1992.
5. J. Liang and T.D.Tran, "Fast multiplierless Approximations of the DCT with Lifting Scheme", *IEEE Trans. on Signal Processing*, pp. 3032-3043, Dec. 2001.