Real-Time Ultrasonic Imaging System Based on Discrete Cosine Transform for NDE Applications

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***Abstract*— This paper presents a unified, hardware efficient architecture for multi-purpose ultrasonic imaging systems. Ultrasonic flaw detection, data compression and denoising applications are implemented within the same framework by integrating a common transform block, discrete cosine transform (DCT). DCT is primarily used for energy compaction properties in compression applications and for frequency decomposition in detection algorithms. Furthermore, recursive DCT implementations based on Clenshaw's formula are presented in order to reduce the hardware requirements of large scale transforms for a feasible real-time SoC architecture.**

Keywords-Compression; DCT; flaw detection; SSP;

I. Introduction

Ultrasonic imaging is a quintessential tool for wide variety of NDE applications and flaw detection. There is an increasing demand for portable, handheld devices that can operate not only in laboratory environments but also in the field. Furthermore, ultrasonic imaging applications require a significant amount of data collection. Consequently, it is desirable to use data compression techniques to reduce data while maintaining the signal integrity. In this study, we present a unified real-time system-on-a-chip (SoC) architecture that can employ both ultrasonic flaw detection and compression algorithms. There are major challenges for the development of portable ultrasonic imaging devices such as requirements for high computational rate, low power consumption and compact size. We address these critical issues with a novel architecture that uses a Discrete Cosine Transform (DCT) kernel as the main transform block. A desirable attribute of DCT is its reduced computational complexity compared to other subband decomposition algorithms such as fast Fourier transform (FFT) and discrete wavelet transform. DCT is used for compression applications due to its excellent energy compaction properties. It has been shown that for ultrasonic signals, DCT can achieve significant compression ratios such as 1:10 with minimal energy loss. DCT can also be integrated into ultrasonic flaw detection applications as an alternative to FFT for split spectrum processing (SSP). DCT based SSP algorithms have flaw-to-clutter (FCR) ratio improvements comparable to FFT based algorithms and can improve the target echo visibility by 10dB or more. Most DCT hardware implementations are parallel architectures based on special factorizations of the DCT kernel in order to minimize the number of multiplications and additions. However, these factorizations are not feasible for large transforms (as required by ultrasonic signals) due to their irregular and non-recursive structures. Therefore, in this study the recursive DCT structures based on the Clenshaw's formula are used for large transform kernel synthesis. Using this method, the resulting DCT structure is comprised of simple IIR filters and uses very limited hardware resources.

In Section 2, DCT kernel and properties are briefly defined. Section 3 describes the ultrasonic imaging system which can employ both detection and compression applications. Flaw detection and compression algorithms utilizing DCT are also presented with experimental results. Section 4 describes the recursive DCT algorithms and implementation for FPGA devices. Results are shown in Section 5.

II. Discrete Cosine Transform

The DCT is an excellent processing tool to perform signal analysis and it is widely used for signal compression applications; such as JPEG (Joint Photographic Experts Group) and MPEG (Moving Pictures Expert Group) for image and video compression. The audio formats AAC, Ogg Vorbis (Vorbis), and the MP3 also uses a modified version of the DCT (MDCT) algorithm based on the overlapping of data. The forward DCT is defined as:

$$X(m) = \sqrt{\frac{2}{N}} k_m \sum_{n=0}^{N-1} x(n) \cos\left(\frac{(2n+1)m\pi}{2N}\right), \quad m = 0,1,\ldots,N-1 \tag{1}$$

where

$$k_j = \begin{cases} 1, & \text{if } j \neq 0 \text{ or } N \\ \frac{1}{\sqrt{2}}, & \text{if } j = 0 \text{ or } N \end{cases} \tag{2}$$

In this paper, DCT algorithm is analyzed for ultrasonic imaging applications including flaw detection, energy compaction (i.e., compression) and denoising properties. We also examine efficient DCT hardware implementations for real-time ultrasound applications.

III. Ultrasonic Imaging Applications

The ultrasonic detection, data compression and denoising algorithms can be integrated into an embedded system as shown in Fig. 1. For a case study, a single FPGA device from Xilinx, Inc is used. This FPGA supports 2 PowerPC hardware processor cores as well as multiple Microblaze software processor cores. PowerPC core handles the control operations as well as the input streaming from a data acquisition unit.

DCT based transform computations are realized through a hardware accelerator block. The accelerator block is configured by the Microblaze core-1 (which has been instantiated with cache memory) for the desired application such as compression or flaw detection. The accelerator unit and the processor core communicate through a fast FIFO type channel called Fast Simplex Link (FSL). Another processor core is in charge of I/O interfaces. This processing unit is applied to the received RF signals (i.e., raw data), also known as the amplitude mode (A-mode or A-scan), which contains the information pertaining to the properties of the propagation path of the ultrasonic beam within the object. Depending on the application, the RF signals are used to compose brightness mode (B-mode, B-scan or 2D ultrasonic image), or motion mode (M-mode which is a display of the vertical positional changes). Furthermore, the appropriate post-processing of the RF signals allows other imaging applications such as flow imaging (Doppler effect), and volumetric (3D) imaging in addition to ultrasonic flaw detection and data compression.

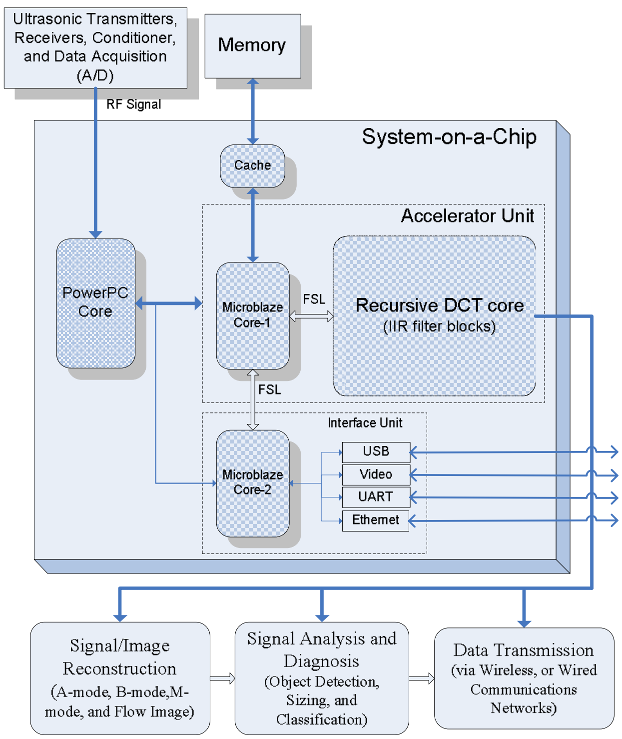

Figure 1. Functional block diagram of ultrasonic imaging system.

A. Ultrasonic Flaw Detection Using DCT

Split-spectrum processing (SSP) of the broadband echoes is an effective method for ultrasonic NDE applications [1]. In Rayleigh scattering, where the signal wavelength is significantly larger than the microstructure of materials that consist of randomly distributed reflectors and grains, the detected echoes exhibit randomness in amplitude and are sensitive to shifts in the transmitted frequency. In contrast, targets are often larger in size and their amplitudes are less vulnerable to variation in the transmitted frequency. Since the clutter echoes are more sensitive to the frequency shifts, it is less likely that these clutter echoes contribute to the same spatial position in all the frequency bands. Therefore, any echo signal that is significantly large and uniformly visible among many frequency channels, originates from a target echo reflector. At any given time, the outputs of bandpass filters can be represented as a random feature vector that contains information related to target and grain echoes.

Fig. 2 shows the SSP implementation where frequency decomposition is achieved by multiple bandpass filters. Conventionally, band-pass filtering is achieved by applying fast Fourier transform (FFT) to the digitized ultrasonic signal and a subsequent windowing operation. However, that DCT can also be integrated into SSP algorithms with comparable flaw detection performance with respect to FFT due to similarities in FFT and DCT transform kernels [2]. Both FFT and DCT transform operations are based on correlation of cosine kernels with the input data. However, DCT offers a significand reduction in the computational complexity since no complex number operations are required. Therefore, DCT presents a more viable hardware architecture for real-time implementations.

Following the DCT based frequency decomposition, flaw echo visibility can be enhanced through post-processing the channel outputs (i.e., signals reconstructed in time-domain). In particular, application of *minimization* post processing algorithm to frequency-diverse ultrasonic target detection works effectively [1]. For the minimization algorithm, minimum amplitudes of the observation channels are obtained for each particular time.

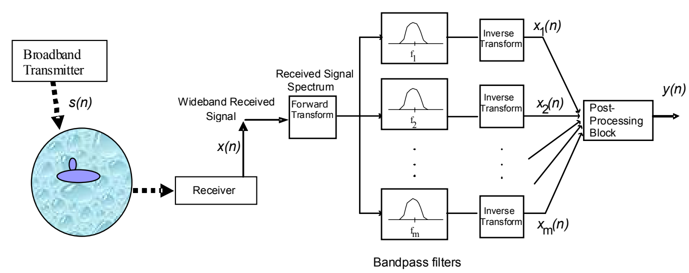

Figure 2. Ultrasonic flaw detection using SSP.

Fig. 3 shows a typical flaw detection result for experimental ultrasonic data. The A-scan measurements were conducted using a steel block and a 0.5 inch transducer with 5 MHz frequency. For both DCT and FFT, 8 different frequency domain windows are used covering the frequency spectrum of the transducer between 0 to 5MHz. The bandwidth of a single frequency window is 3MHz and the overlap between the successive windows is 0.3MHz. Input data size N is equal to 1024 data points. For performance analysis, flaw-to-clutter ratio (FCR) is evaluated using SNR as performance criteria. SNR is calculated by finding the maximum flaw echo amplitude in the reconstructed signal. This value is compared with the largest amplitude of clutter echoes. Examining Fig. 3, it can be seen that the flaw echoes inside the steel block are made clearly visible by suppressing the clutter echoes using DCT based SSP algorithm. DCT improves the FCR approximately by 10dB based on multiple experimental data simulations.

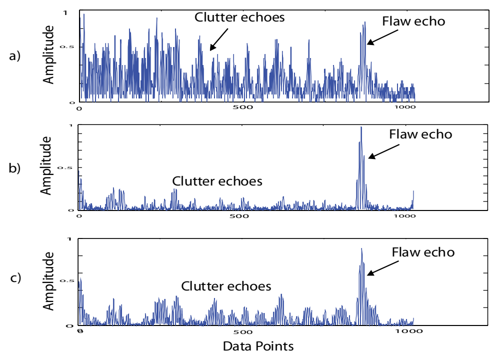

Figure 3. Ultrasonic flaw detection performance using SSP: a) experimental signal b) detection using FFT c) detection using DCT

B. *Ultrasonic Data Compression Using DCT*

Discrete transforms such as DCT, discrete wavelet transform (DWT) and Walsh-Hadamard (WHT) are used in data compression and denoising applications due to data decorrelation and separation properties of the transforms. This separation is especially useful for denoising purposes if the transform is able to split the information content of the signal from the noise content in the transform domain. With a proper transform method, the energy of the transform coefficients can be more concentrated than the time domain samples. Hence, data compression can be achieved as the low energy coefficients are discarded (i.e., data reduction). The dominating coefficients are then used to reconstruct the original signal with some loss of information. Other important characteristics of transforms are data independence (i.e., same transform kernel can be used for different types of data) and computational speed.

The data compression of a given signal *x(n)* is successful when the redundant and noise components of *x(n)* are reduced or removed. The signal $\hat{x}(n)$ is the compressed representation of *x(n)*. Thresholding can be applied to transform coefficients of the original ultrasonic signal for data compression. In hard thresholding method, all coefficients smaller than τ are set to zero. All coefficients greater than τ are kept same.

$$\hat{X}(n) = \begin{cases} 0, & X(n) < \tau \\ X(n), & X(n) \geq \tau \end{cases} \tag{3}$$

For a signal corrupted by White Gaussian Noise with variance σ^2, it has been shown [3] that the optimal threshold for N number of sample points is:

$$\tau = \frac{\sigma}{\sqrt{N}}\sqrt{2.\ln(N-1)} \tag{4}$$

This threshold value can be used as the initial threshold value. Based on the compression ratios achieved, this value can be adjusted dynamically.

The compression performance of the DCT, DWT, and WHT with respect to the ultrasonic echo bandwidth (i.e., NBW) is shown in Fig. 4 [4]. All signals are 512 16-bits samples long. Fig. 4 displays the reconstructed signals when the 25 most dominant coefficients (95% compression ratio) are used in the inverse transforms for a broadband (NBW=0.5) and a narrowband (NBW=0.1) signal. For a broadband signal (NBW= 0.5) the DWT Daub20 outperforms the DCT and WHT, as the DWT coefficients are able to recover over 90% of the signal energy. The DCT outperforms the DWT and WHT for narrowband signals (NBW= 0.2). The results suggest that the DWT may better represent broadband signals, while the DCT may better perform in representing narrowband signals.

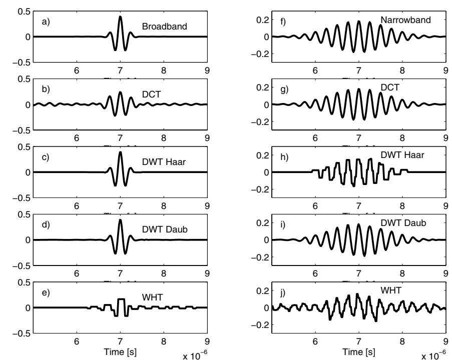

Figure 4. a) Broadband signal, b) ultrasonic signal compressed 95% using DCT, c) DWT (Haar), d) DWT (Daubechies), e) WHT; f) Narrowband signal, g) ultrasonic signal compressed 95% using DCT, h) DWT (Haar), i) DWT (Daubechies), j) WHT [4]

In ultrasonic imaging, the physical parameters (center frequency, time-of-arrival, and amplitude) governing the behavior of backscattered echoes are used for diagnostic images, target detection, deconvolution, object classification, velocity measurement, and ranging systems. Hence, the compression of the ultrasonic signals must offer not only high data reduction ratio but must also allow reconstructing the signal with high fidelity. DCT presents a viable solution in terms of preservation of signal integrity, compression rate and computational complexity for compression ratios such as 1:10.

IV. HARDWARE REALIZATION FOR DCT BASED ULTRASONIC IMAGING APPLICATIONS

The repetition rate in ultrasonic imaging systems dictates the processing time for real-time applications. For real-time systems, a typical value for a repetition rate is 1000Hz resulting in 1ms time intervals for processing the acquired data. Fig. 5 shows the timing requirements for a typical application. Data acquisition takes 10s (considering 1K samples acquired at 100 MHz sampling rate). Consequently, target detection /compression system has to process the data, store the results and either display, or transmit the processed results in 990s.

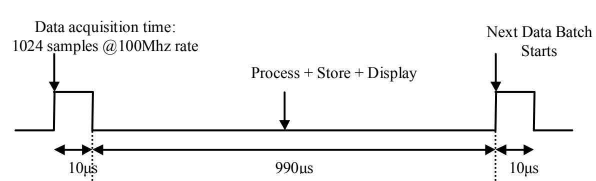

Figure 5. Timing Diagram

Depending on the ultrasonic imaging application, multiple forward and inverse DCT transforms need to be executed within this timing constraint. However, parallel implementation of fast DCT algorithms is impractical when the transform is very large. Although the algorithms given in [5] and in particular [6] have small number of arithmetic operations, they do not scale easily to 1024 point DCT transform. An alternative method is using recursive structures [7,8]. These recursive implementations have very regular VLSI structures that are especially suitable for large transforms (N>128) as is the case in our applications. Therefore, ultrasonic imaging system described in Fig 1. utilizes a hardware accelerator block dedicated to DCT transform implementation. This accelerator unit is based on IIR filters for recursive DCT implementation.

A. *Recursive DCT*

Based on the Clenshaw's formula [7], (1) can be rewritten as:

$$X(m)=\sqrt{\frac{2}{N}}k_m(-1)^m\cos\left(\frac{\theta_m}{2}\right)[a_{N-1}-a_{N-2}] \quad (5)$$

$$a_{-2}=a_{-1}=0;\ \theta_m=\frac{m\pi}{N}; \quad (6)$$
$$a_n=2\cos\theta_m a_{n-1}-a_{n-2}+x(n) \quad (n=0,1,...,N-1)$$

Therefore, a_n is recursively generated from input sequence *x(n)* and at the *N*th step, *m*th DCT coefficient is calculated. IIR filtering is used to obtain the recursive DCT coefficients.

B. *Folding Architectures for Recursive DCT*

Although hardware requirements are basic for the recursive structure given in (5) and (6), computationally it requires N^2 clock cycles for *N* data points. In [8], faster recursive structures have been presented to improve computation time. These structures employ folding operation where only half of the summation terms are required to express *X(m)* by exploiting the symmetry properties of the cosine terms. Furthermore, even and odd inputs can be processed separately with additional IIR filter blocks. The folding operation takes place in the pre-processing step. Single folding operation can be described as:

$$w_m[n]=x[n]+(-1)^m x[N-1-n];\ \ (\mathrm{n}=0,1,...,\mathrm{N/2}-1) \quad (7)$$

When *m* is even, the DCT coefficient *X[m]* is given as:

$$X[m]=\sqrt{\frac{2}{N}}k_m\cdot(-1)^{m/2}\cdot g_{N/2-1}(m) \quad (8)$$

$$g_j[m]=\cos\frac{\theta_m}{2}\{w_m[j]-w_m[j-1]\}+2\cos\theta_m g_{j-1}(m)-g_{j-2}(m) \quad (9)$$

When *m* is odd, DCT coefficient *X[m]* is given as:

$$X[m]=\sqrt{\frac{2}{N}}k_m\cdot(-1)^{(m-1)/2}\cdot h_{N/2-1}(m) \quad (10)$$

$$h_j[m]=\sin\frac{\theta_m}{2}\{w_m[j]-w_m[j-1]\}+2\cos\theta_m h_{j-1}(m)-h_{j-2}(m) \quad (11)$$

Fig. 6 shows the IIR filters used for even and odd DCT coefficients. With two IIR filter kernels, two DCT coefficients are computed in parallel by only *N/2* computational cycles.

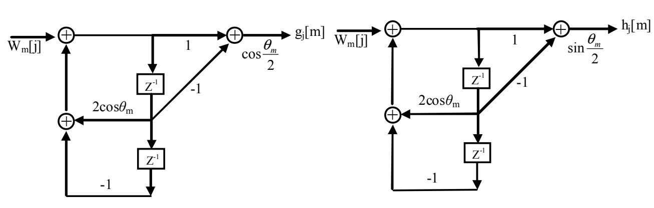

Figure 6. Recursive DCT structures a) even coefficient b) odd coefficient

Folding can be applied twice, resulting in double folding architectures with further reduction in computational cycles at the expense of more complex input processing unit. The IIR filter structure is same as filters shown in Fig. 6. Only *N/4* computational cycles are required for computing two DCT coefficients.

V. RESULTS

Recursive DCT kernels are implemented using System Generator, a Xilinx software tool for schematic entry and VHDL interface to MATLAB. Table I shows the synthesis results for Xilinx Virtex2pro (xc2vp30-7) FGPA device. While all the recursive architectures easily fit into the design, throughput values (i.e., the total clock cycles and maximum clock speed) are significantly different. In particular, double folding method achieves an almost ten times more throughput compared to the original recursive implementation.

TABLE I. IMPLEMENTATION RESULTS FOR RECURSIVE DCT

Recursive Architectures	**Performance**			
	Num. of clock cycles	***Datapath delay***	***Max. Frequency***	***Area[1]***
No folding	N^2	19.63ns	50.83MHz	144,222
Single folding	$N^2/4$	16.76ns	59.66MHz	416,452
Double Folding	$N^2/8$	16.80ns	69.50MHz	697,158

1. Total equivalent gate count for design)

VI. CONCLUSION

In order to meet the computational demands of real-time ultrasonic imaging applications, we design and synthesize an embedded system based on recursive DCT implementation. Performance results and FPGA synthesis benchmarks support the feasibility of DCT-based architectures for real-time ultrasonic imaging applications.

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