A Comparison of the Lookup Table and On-The-Fly Calculation Methods for the Beamforming Control Unit

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Abstract: Modern diagnostic ultrasound beamformers require extensive delay information for the focusing of each focal point along the image lines. For a typical beamforming system with dynamic delays, the beamforming control unit is used to calculate the delay information and generate instant delay profiles in order to achieve dynamic focusing beamforming. In this study, the beamforming control unit targeted at a home-based portable delta-sigma oversampled ultrasound beamforming setup was developed. The beamforming principle for 1-D linear transducer array with dynamic aperture was exploited, and three delay generation methods including complete lookup table, compressed lookup table with delta encoding and general parametric algorithm were investigated, implemented and synthesized using VHDL for a FPGA device Spartan-3E XC3S500E. A comparison was performed among the three delay generation methods on their performances in terms of overall logic resource usage and power consumption.

1. Introduction

Ultrasound has been used as a means of medical imaging since late 1940s, and since then medical diagnosis is greatly facilitated as the application of ultrasound is being expanded to more functions. In medical ultrasound imaging, the vast majority of the diagnostic images are produced line by line. A group of transmitting elements on a transducer array is fired at a time to form an image line, and a number of receive processing channels perform digital focusing along the image lines as the transmitted wave propagates in depth. The processing is called beamforming [1]. For the purpose of maintaining focus as the focal depth increases, the delay applied to the received echo signal samples on different channels has to be updated for every clock cycle. For a typical ultrasound beamforming system, the beamforming control unit is designed to calculate delay information and generate instant delay profiles in order to achieve dynamic focusing beamforming [2].

As ultrasound imaging system is safer and easier to operate compared to other imaging machines, the incentive to develop it for home use is strong. In this study, a home-based portable delta-sigma oversampled ultrasound beamforming setup with dynamic delays was targeted. The oversampled beamformer employs 64 receive processing channels, with each channel consisting of 144 memory cells, operating at an oversampling frequency of 160MHz.

The beamforming principle for 1-D linear transducer array with dynamic aperture was exploited as the foundation for delay information calculation, and three delay generation methods including complete lookup table, compressed lookup table with delta encoding and general parametric algorithm were investigated, implemented and synthesized using VHDL for a FPGA device Spartan 3E XC3S500E. A comparison among the three delay generation methods on their performances in terms of both logic resource usage and power consumption was performed and the implementation results will be presented in this paper.

2. Receive Beamforming Principle

Although there are several different transducer array schemes available each having different elevation resolutions, 1-D linear transducer array is adequate to provide satisfactory image resolution with the pre-set oversampling frequency. A group of 64 transmitting elements on the transducer array are activated and fired at a time to form an image line or scanline. The active element group is then shifted by one element at a time across the whole transducer array to scan over the area covered by the transducer. During receive mode, the reflected ultrasound echoes from a certain focal point reaches each transducer element at different time instants due to the difference in the geometric distance. Hence, beamforming is applied to select the received echo signal samples lying on the same delay profile for coherent summation.

2. 1 Delay calculation

The images produced by contemporary ultrasound scanners consist of straight image lines originating from the transducer surface. According to the delay calculation geometry shown in Figure 1, the instant delays that are applied to generate a dynamic receive focus can be calculated using:

$$p = d_f + d_r = 2d_f - x_n \sin\theta + \frac{x_n^2 \cos^2\theta}{2d_f} \qquad (1)$$

where p is the full pulse-echo path, d_r is the length of the echo path, d_f is the instant focal depth measured from the beam origin of the transducer to the focal point, x_n is the distance from the centre of the transducer array to the n^{th} element, and θ is the steering angle.

Time of flight can be calculated by dividing p with the speed of sound in the medium. For linear transducer array, $\theta = 0°$ as there is no steering, which implies the same set of delay profiles can be shared by all image lines. Furthermore, as beamforming can be viewed as selecting the correct samples for a given focal depth from different channels, each pair of the receive processing channels are symmetrical about the centre of the transducer array and they share the same delay patterns for their stored echo signal samples.

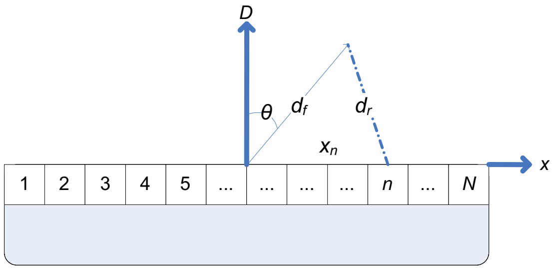

Figure 1. Delay calculation geometry for 1D linear transducer array.

2. 2 Dynamic aperture

Aperture size of the transducer can be varied with the focal depth in order to achieve homogenous signal strength and uniform point spread function. This is called dynamic aperture, which is commonly used in beamforming. The transducer aperture is gradually opened up from the central receive processing channels according to a parameter called *f*-number, which is the ratio of the instant focal depth over the size of the aperture as defined in Equation (2).

$$f = \frac{d_f}{(N-1)\Delta x} \tag{2}$$

where d_f is the instant focal depth, N is the number of active channels and Δx is the pitch between adjacent transmitting elements on the transducer array.

It has been found that optimal focusing performance can be achieved when the *f*-number is greater than or equal to 1.5 [3]. In other words, when the focal depth increases, the number of active channels is gradually increases to ensure that the instant focal depth is always 1.5 times greater than or equal to the width of the opened aperture, until all the channels have been activated.

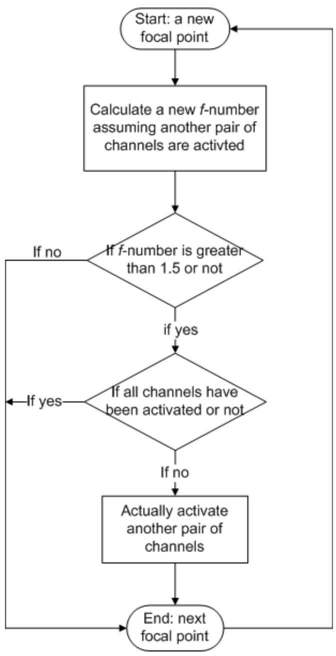

Figure 2. Flowchart of the dynamic aperture mechanism.

Figure 2 illustrates the flowchart of the dynamic aperture mechanism. The checking mechanism is executed once for every focal depth and always begins a trial by pretending that another pair of receives channels have just been activated. A new value of the *f*-number can be therefore calculated and compared with 1.5. If the *f*-number is found to be greater than 1.5 and there are still inactivated channels connected to the transducer array, then another pair of channels will be actually activated in order to minimize the difference between the focal depth and the aperture size. If either of the two conditions is not satisfied, the transducer aperture will remain its current size.

3. Lookup Table Approaches

3. 1 Complete lookup table method

The complete lookup table method is designed to replace the extensive run-time calculation of instant delay profiles by a simple lookup operation, however, at the cost of the memory usage due to the storage of the pre-generated delay patterns for each processing channel. All the delay information necessary for performing dynamic focusing was pre-calculated according to the beamforming principle presented in Section 2, and stored in complete form into a data structure, usually implemented by register arrays or read-only memory (ROM) modules. As shown in Figure 3, during delay update operation, the pre-stored delay values stored in the ROM module are accessed with read operations according to current focal point index. The ultimate output of the beamforming control unit takes the form of memory addresses as applicable delay data such that the desired echo signal samples can be properly selected from variable length delay lines, which are implemented by using memory elements.

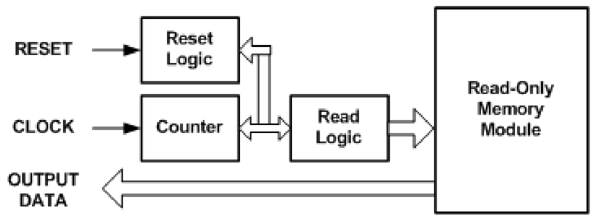

Figure 3. Block diagram of the complete lookup table approach.

3. 2 Compressed lookup table with delta encoding

The amount of necessary focusing information is large, since delay information for all receive channels for all focal depths has to be stored. Keeping it in an uncompressed form requires significant size of memory, and researchers have been working on approaches for compression since the introduction of digital beamforming. In order to avoid storing large amount of address data, the delta encoding scheme was employed to compress the conventional lookup table. By applying delta encoding, only the differences between the delay (index) values instead of the absolute delays were stored in the lookup table [1]. With the instant increment of focal depth, Δ, specified as half wavelength, λ

($\lambda = c \cdot T_s$, where c is the speed of sound and T_s is the sampling period), the original n-bit-wide delay words can be represented by single bits, thus reducing effectively the size of the lookup table. To recover the n-bit-wide delay addresses, accumulation operation is incorporated after the read process to add up the address difference stored, as shown in Figure 4.

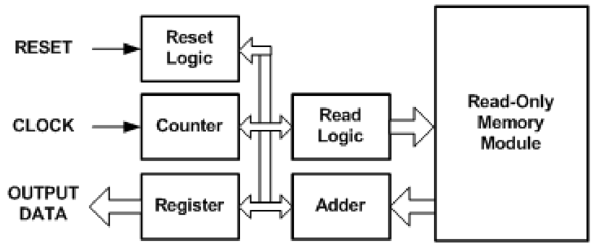

Figure 4. Block diagram of the compressed lookup table with delta encoding approach.

The run-time calculation involved in delta encoding is minimal, as only an adder is needed to add the current relative delay read from the lookup table to the previous output address stored in a register.

4. General Parametric Approach

In contrast, rather than storing the pre-generated focusing information in a lookup table, the general parametric method calculates the instant delay profile with on-the-fly calculation in the run time. The general parametric approach utilizes the nature of the focusing delay curves by describing the delay curve using a quadratic equation:

$$f(p_N, d_N) \equiv p_N^2 - 2d_N(p_N - k_N) - x_N^2 = 0 \quad (3)$$

which was derived from Equation (1) by dividing both sides with Δ^2. The term $k_N = x_n \cdot \sin\theta$ is constant for a given image line inclination and transmitting element [1]. The index N denotes that the variable unit is quantized and is an integer.

In the general parametric algorithm, the function to be evaluated is $f(p_N, d_N)$. To approximate the delay curve, the delay generation logic has to keep $f(p_N, d_N)$ as close to 0 as possible, therefore it should increase p_N by 1 or 2 for each unit increase of d_N. The choice is made by evaluating the sign of the function $f(p_N + 1, d_N + 1)$. It can be seen that:

$$f(p_N + 1, d_N + 1) = f(p_N, d_N) - 2d_N + 2k_N - 1 < f(p_N, d_N)$$

and

$$f(p_N + 2, d_N + 1) = f(p_N, d_N) + 2p_N - 4d_N + 2k_N > f(p_N, d_N) .$$

Therefore, a step-by-step delay algorithm can be built around the equation by numerically solving it at each increment of a leading variable, which is the instant focal depth d_N in this case.

1. The initial values $d_N(1) = d_{start}\frac{f_s}{c}$, $p_N(1) = p_{start}\frac{f_s}{c}$ and $k_N = x_n \sin\frac{f_s}{c}$ are applied.
2. If $f(p_N + 1, d_N + 1) > 0$, then $p_N(n + 1) = p_N(n) + 1$, else $p_N(n + 1) = p_N(n) + 2$.
3. $d_N(n+1) = d_N(n) + 1$, and if the end of the line is not reached, go back to 2 [1].

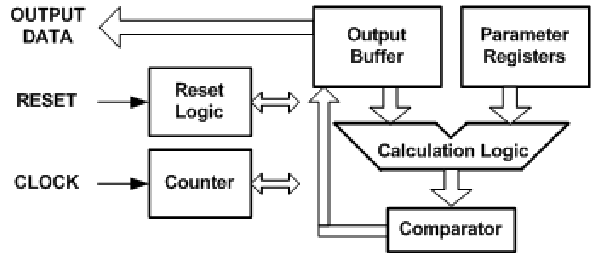

Figure 5. Block diagram of the general parametric on-the-fly calculation approach.

The general parametric algorithm generates output with a maximum error of ±1 units. Since a single unit is corresponding to the distance that ultrasound waves travel in half clock period, the precision of this method is therefore ±½ clock periods, which is relatively more accurate compared to the two lookup table methods presented in Section 3. The precision of both the conventional and compressed lookup table methods can only be up to one clock period, as the computation unit used for the delay calculation of the two lookup tables was normalized to be a full wavelength λ.

A pipelined design was employed for the implementation of the described algorithm in order to increase the throughput and also to ensure the timing constraints imposed by the real-time system being satisfied. The resulting implementation requires only a few input parameters, but has the disadvantage of consuming power and logic resource due to the implementation of the on-the-fly calculations.

5. Implementation Results and Discussions

A comparison between the three delay generation methods for the beamforming control unit targeted at the home-based portable oversampled ultrasound beamformer was done. The sampling frequency was set to be 160MHz for the purpose of consuming reasonable amount of power while achieving good focusing. The occupied logic gate count and power consumption were estimated for the VHDL implementation of the three methods in an FPGA for a target device Spartan-3E XC3S500E by Xilinx. The same level of optimizations was achieved for the three designs. The synthesis results for the three delay generation approaches are shown in Table 1.

Table 1. Implementation results of (a) complete lookup table approach, (b) compressed lookup table with delta encoding approach and (c) general parametric approach.

	Logic gates	Power@160 MHz
(a)	1738	240.88 mW
(b)	1539	233.58 mW
(c)	3369	261.05 mW

It can be seen that the general parametric approach occupies most logic gate count and most power among the three methods, due to (i) the run-time calculations of the instant delay profile, which dissipates significant computing power and (ii) the inefficiency of implementing calculation logics compared to memory modules in FPGA, as shown in Table 2.

Table 2. Device utilization of (a) complete lookup table approach, (b) compressed lookup table with delta encoding approach and (c) general parametric approach.

	Slices registers	4 input LUTs
(a)	16	177
(b)	28	191
(c)	220	220

On the other hand, the compressed lookup table with delta encoding approach has the best performance in terms of overall logic resources as well as power consumption. The reduction of logic gate count by applying delta encoding in FPGA is only marginal, because the same ROM module was used to store the lookup tables for the two approaches after examining their respective RTL schematics. In other words, despite the difference in word width, the size of both lookup tables is the same, which is equal to the total number of focal depths along an image line. However, for more sophisticated imaging systems such as 3D transducer with higher resolution, which require considerable memory size for their more complex focusing information, the on-the-fly calculation approach might still be advantageous.

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