Abstract

The beamforming performance of conventional Linear Phased Array (LPA) Ultrasonics depends heavily on the geometric structure of its adopted LPA transducer array. In order to achieve good imaging quality, the number of elements arranged in half wavelength distance and their corresponding hardware resources are very demanding. In this paper, a challenge goal was set to develop a small-scale portable Ultrasound Testing Imaging Instrument that has the necessary imaging quality in terms of high contrast, high clarity and improved resolution. An advanced beamforming method was proposed based on a 16-element linear array. The creative strategies were designed in the way of combining Synthetic Transmit Focusing-Dynamic Receive Focusing (STF-DRF) with adaptive coherent weighting. The new method is not only capable of producing an acceptable compromise between front-end HW complexity and inspection imaging quality, but also effectively suppresses unwanted interference from undesired directions, which are inherently introduced by high-level side-lobes in the beam profile pattern of small-size arrays.

Keywords: Adaptive imaging, Phased array, synthetic aperture focusing, coherent weighting

1. Introduction

Since Linear Phased Array (LPA) techniques were available in the NDT industry, the simple Delay-and-Sum (DAS) beamforming technique had been widely used in LPA ultrasonic imaging. The conventional LPA beamforming performance strongly depends on the geometric structure of an adopted LPA transducer array. The Point Spread Function (PSF) of beamforming imaging, the key factor to the spatial resolution of imaging inspection, is mainly determined by the beam-pattern production between the transmission array and the receive array [1,2]. A large size array containing a significant number of elements (for example, an array with over one-hundred elements) is capable to produce a reasonable narrow-beam pattern profile, which provides high spatial resolution performances. However, the obtained attractive beam profile is at the expense of higher complexity in front-end hardware due to large number of parallel channels, which results in higher power consumption and a higher-cost product. These major drawbacks are generally not acceptable.

Many efforts had been made by researchers and engineers on developing a high-performance, small-scale, portable instrument based on LPA. Recently, GE Inspection Technologies has successfully implemented an advanced beamforming technique: Synthetic Transmit Focusing and Dynamic Receive Focusing (STF-DRF) based on an LPA product. A small-size array composed of 16 elements was adopted. These new beamforming techniques showed excellent capabilities to produce a very good compromise between front-end hardware complexity and inspection imaging quality. Due to the small scale of array with less number elements contained, the point spread function of transducer aperture still inherently presents the drawback property such as high-level side-lobes, by which the unwanted interferences from undesired directions are unfortunately introduced and show up as high-level background noise. The imaging quality was unavoidably degraded.
In order to achieve a high-quality imaging inspection instrument, we proposed an innovative adaptive imaging method that combines STF-DRF beam-steering sector-scan imaging with adaptive coherent measurement weighting strategy. It provides a set of advantageous characteristics, such as small-size aperture, acceptable sensitivity-detecting capability and adaptive-coherent weighting.

2. Ultrasound Beamforming Imaging Techniques

The process of forming a spatial beam through beamforming methodology can be understood in the way of designing a high-performance spatial filter. The goal of the beamforming process is to construct a spatial filter with distinct capability, which is capable to optimally extract the defect-reflected signals from the desired direction, meanwhile efficiently suppressing unwanted signals reflected from all non-interesting directions.

2.1 Linear Phased Array (LPA) UT Imaging Techniques

Linear-array transducers are commonly used in Phased Array Imaging systems. In a typical linear-array imaging method, a group of transducer elements, commonly referred to as a virtual probe, are active during incidence pulse formation and/or pulse reception from the specimen. The simplest DAS focal law is often the basis of the beamforming imaging algorithm; the programmable electronic delay enabling sweep scan or sector scan imaging.

Based on the DAS principle, the premier beamforming is Confocal-Transmit-Receive Imaging. These techniques are used by the most current products in the market. The improvement was gained by using multiple receive-focusing zones instead of single fixed-receive focus. Further improvement efforts were generated by adopting Multiple-Transmit-Fixed-Focusing-Zones and Dynamic-Receive-Fixed Imaging, which is recognized as a better solution since it is close to fully-dynamic transmit-and-receive focusing. However, the increased number of firing events required for multiple-transmit zones significantly affects the frame rate.

![Figure 1: Schematic representation of PA sector-scan imaging.](image-url)
For each individual scanned position, the defect-reflection signals from angle direction $\alpha$ are received by all channels. By means of time-delay compensation for the acoustic wave round-trip time of flight, the defect signals are processed.

The extracted signals are then converted into the pixel intensity at the corresponding positions in the scanned image. With RF received signal $S$, the beamforming pixel’s intensity can be described as:

$$P_{x,z} = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{i,j} (t - \tau_{\text{Trans}(i)}(x,z) - \tau_{\text{Rev}(j)}(x,z))$$  

(1)

$\tau_{\text{Trans}(i)}(x,z)$ is the $i^{th}$ transmitting element beamforming delay and $\tau_{\text{Rev}(j)}(x,z)$ is the $j^{th}$ receive element beamforming delay with regard to the imaging pixel location at $(x, z)$. The first summation (with index $i$) and the second summation (with index $j$) are for transmitting beamforming and receive beamforming respectively. The calculation for $\tau_{\text{Trans}(i)}(x,z)$ and $\tau_{\text{Rev}(j)}(x,z)$ depends on the beamforming method.

### 2.2 Synthetic Fixed Focus Transmit with Dynamic Receive Focusing (STF-DRF)

In this method, a sub-aperture is used to fire the pulse into the specimen instead of a single element as in the classic synthetic-aperture technique, while all elements (N elements) in the whole array are active for collecting the received signals. The sensitivity, the penetration depth, or signal-to-noise ratio is increased for each round-trip data processing.

The STF-DRF beamforming method for extracting echoes from steering angle direction $\alpha$ can be prescribed as:

$$P_{x,z} = \sum_{k=1}^{L} \sum_{i=1}^{M} \sum_{j=1}^{N} S_{i,j} (t - \tau_{\text{Sub}(k)\text{Trans}(i)}(x,z) - \tau_{\text{Sub}(k)\text{Rev}(j)}(x,z))$$  

(2)

The first summation (index by $k$) is for the $L$ sub-apertures synthetic array transmission, the second summation (index by $i$) is for the summation of the transmit beamforming, and the third summation (index by $j$) is for the receive beamforming.

### 2.3 Adaptive-STF UT Imaging Based on LPA

In our proposed adaptive imaging processing, for each individual transmit sub-array firing, the dynamic receive focusing qualities are constantly evaluated with regards to each specified steering angle. The Coherent Factor is introduced and defined as $CF_{\text{Sub}(x,z,t)}$ as shown below. $M$ is the number of active transmit elements in each transmitting sub-aperture, while $N$ is number of active receive elements in the receiving aperture. Here, $N$ equals to the number of all elements in the entire array. The output of the Adaptive STF-DRF beamforming is obtained by:

$$P_{x,z} = \sum_{k=1}^{L} CF_{\text{Sub}(k)}(x,z,t) \sum_{i=1}^{M} \sum_{j=1}^{N} S_{i,j} (t - \tau_{\text{Sub}(k)\text{Trans}(i)}(x,z) - \tau_{\text{Sub}(k)\text{Rev}(j)}(x,z))$$  

(3)

For $k^{th}$ transmitting sub-aperture, set the $j^{th}$ element received time-delay compensated signal as:

$$S_{\text{Sub}(k),\text{Rev}(j)}(t - \tau_{\text{Sub}(k)\text{Rev}(j)}(x,z)) = \sum_{i=1}^{M} S_{i,j} (t - \tau_{\text{Sub}(k)\text{Trans}(i)}(x,z) - \tau_{\text{Sub}(k)\text{Rev}(j)}(x,z))$$  

(4)
The coherent factor, which plays a role for evaluating the alignment quality of all received time-delay compensated signals, is introduced as below, where: \( j \in N \)

\[
CF_{sub(k)}(x, z, t) = \frac{\sum_{j=1}^{N} S_{sub(k),re(f)}(t - \tau_{sub(k),re(f)}(x, z))}{N \times \sum_{j=1}^{N} |S_{sub(k),re(f)}(t - \tau_{sub(k),re(f)}(x, z))|^2}
\]

(5)

The Coherent Factor \( CF_{sub(k)}(x, z, t) \) can be interpreted in terms of the spatial coherent confidence ratio. It is calculated as the percentage of coherent energy in the total energy collected based on the time-compensated received signals from all receive elements. Its value is ranged within [0 ~ 1]. A higher-ratio value indicates a higher percentage of coherent energy contained in the total collected signal energy, therefore the higher confidence of good focusing quality or correctly aligned focusing. The final extracted signal can be obtained by:

\[
P_{t,z} = \sum_{k} CF_{sub(k)}(x, z, t) \sum_{j=1}^{N} S_{sub(k),re(f)}(t - \tau_{sub(k),re(f)}(x, z))
\]

(6)

Through applying the adaptive coherent measurement weighting, the in-phase signals were strongly emphasized by the high adaptive coherent confidence ratio, while the out-of-phase signals were significantly suppressed by a low ratio.

### 3. Experimental Test with Adaptive-STF UT Imaging Based on LPA

An experimental test had been carried on an aluminum block as shown in the picture in Figure 3. Its measured size is 43mm×78mm×49mm. It has 25 side-drilled holes of 1 mm diameter in a band and an arc and also has 24 holes of 0.8 mm diameter towards one of the corners showing the letters P and A. All the holes are 20 mm deep.

**Figure 2:** Confocal-Transmit-Receive Image of the aluminum test block

**Figure 3:** Photograph of the aluminum test block
The corresponding Confocal-Transmit-Receive Imaging result is shown in Figure 2, and the improved imaging result of Adaptive Beamforming method was shown in Figure 4.

![Figure 4](image)

**Figure 4:** Adaptive LPA Ultrasound Image of the aluminum test block

From the side-drilled-hole defects detected while imaging the aluminum test block shown in Figure 4 clearly illustrates that the defects are more conspicuous and easily identifiable through the new method of imaging. The image contrast had been significantly increased. The highly-clarified image enables the operators to be more confident in identifying defects in the test piece.

4. Conclusions

The proposed innovated method is capable of producing a clean, high-resolution and high-contrast image by introducing adaptive-coherent weighting. From the experimental imaging results, it shows the new method has made an effective impact on suppression of interference introduced by the side-lobes of the LPA transducer. The image resolution in the lateral dimension is improved. Defect signals were weakened which can be compensated by the proper setting of the time-gain-control curve. The improved instrument imaging performance provides users with more confidence when interpreting UT inspection results.

5. Reference