Multi-Aperture Beamforming for Automated Large Structure Inspection using Ultrasonic Phased Arrays

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Abstract. Increasing the inspection quality and speed is essential in manufacturing applications, especially for large structures (e.g. modern aircrafts). Traditional ultrasonic manual scanning can be comprehensive, but lacks repeatability and is time-consuming. Several robotic non-destructive testing systems have been developed in recent years. Although high inspection rates have been achieved by the use of robotic arms, there is the need to furtherly increase the inspection speeds, to cope with the current industrial demands. For systems delivering robotic ultrasonic inspection through phased array probes, the current bottleneck is given by the time required to electrically fire all elements of the phased array probes, which limits the maximum scanning speed of the automated manipulators. This paper discusses the development of a multi-aperture beamforming method to focus the beam with multiple focusing points at a single firing. This work investigates this approach and the influence of different aperture excitations on the data quality. Experiments have been carried out using a 5MHz 32-element phased array probe manipulated by a KUKA robot. The results highlight the possibility to significantly improve the speed of automated inspection compared to linear beamforming, without compromising the inspection quality.

INTRODUCTION

Ultrasound inspection has been widely used for non-destructive testing (NDT) and evaluation, especially in the aerospace and energy industries. It has been demonstrated that ultrasonic phased array probes can speed up the inspection of large parts with complex geometries, since phased array probes have a wider active area than single element probes. Manual inspection using phased array for the large structures is time consuming, especially for the large structure components like plane wing and wind turbine blade. Therefore, robotic platforms (robots, drones) combined with the NDT sensors have been used [1-4]. Achieving high data acquisition speeds, allowing high frame rates for phased array probes and faster robotic inspection speeds, is one of the key challenges to be solved. A paintbrush method was proposed for the aerospace wing structure inspection, however the simultaneous firing of all elements at once produces unfocused ultrasonic beams and poor scanning resolution [1].

The work presented here is a multi-aperture excitation approach to increase the frame rate which is to excite more than one aperture in a single pulse. The multi-aperture beamforming was evaluated on a steel block and the maximum robotic scanning speed was assessed.

LINEAR BEAMFORMING

The linear beamforming for phased array is a typical method to focus the ultrasound energy at the specified depth. The pulses are excited and received by an aperture with a number of elements in the phased array, the delay time of each individual element is controlled by the focal law, the next pulse is formed by moving the transmitter and receiver by shifting certain elements (Normally only one element is shifted to guarantee the lateral resolution). A frame consists of all the pulses generated by the excitation of all elements in an array. The total number of pulses in a frame (N_{pulse}) depends on the number of element in an array (N_{array}) and the number of elements in an aperture (N_{aper}). For example, if an 8 elements aperture is used in the 32 elements array, it results $N_{pulse} = N_{array} - N_{aper} + 1 = 25$ (Fig. 1). However, for each pulse, only one aperture is used in the array, which greatly limits the frame rate.

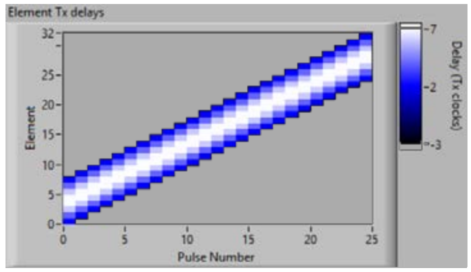


FIGURE 1. Linear beamforming transmit focal law for phased array

MULTI-APERTURE EXCITATION

A different approach is applied to increase the frame rate, which is to use more apertures in a single pulse. The number of pulses per frame for multi-aperture is determined by N_{aper}, N_{array} and the number of gap elements between apertures N_{gap}, which is inserted between two adjacent apertures to reduce the interference level between the neighboring apertures. As shown in Fig. 2, when the first pulse has 3 apertures with 4 gap elements and 8 elements aperture, the total number of pulses reduces from 25 to 12. If no gap is left between the neighboring apertures, then N_{pulse} = 8. Obviously, the number of elements that can be excited simultaneously in a phased array controller determines the aperture number in a single pulse. For a 32-channel system, up to 4 apertures can be excited in a pulse.

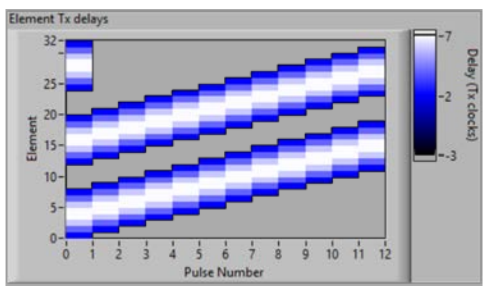


FIGURE 2. Multi-aperture beamforming transmit focal law for phased array

MULTI-APERTURE EXPERIMENT

The multi-aperture experiment was done on a 75mm thick steel block with a 3mm side drilled hole using 8 elements aperture phased array by changing the gap from 0 to 8 elements (Fig. 3). The phased array probe had a center frequency of 5MHz and a pitch of 0.7mm.

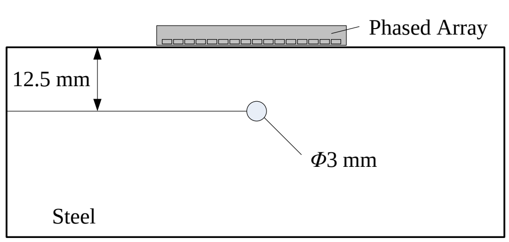


FIGURE 3. Multi-aperture experiment on a steel block

The first B-scan image from the left hand side in Fig.4 is acquired using linear beamforming, and is herein referred as the reference result. The interference of the neighboring beams produces visible artifacts when $N_{gap} = 0$. As the gap between the apertures increases, the interference level reduces, but the number of needed pulses increases. The cross section signal of the 3mm hole in the B-scan image were extracted.

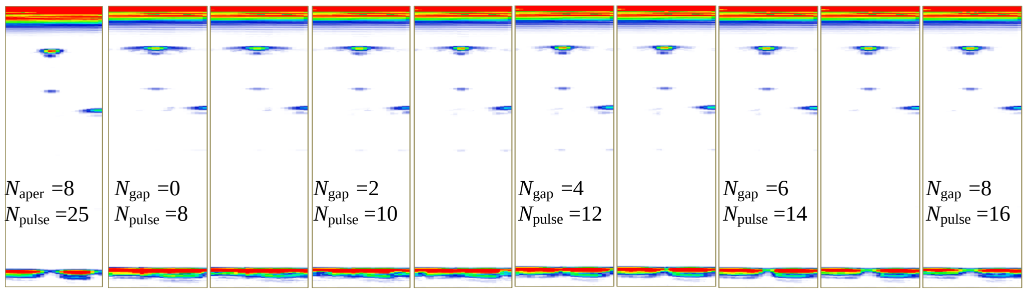


FIGURE 4. B-scan images of a 3mm hole using linear beamforming and multi-aperture excitation

The correlation coefficient is used to evaluate the difference of the multi-aperture excitation and linear beamforming (Fig. 5). The -6dB width estimation of the hole becomes more accurate when the gap increases. The bottom echo signal is different between linear beamforming and multi-aperture in Fig.5c, because the bottom reflection of neighboring pulse is also received for multi-aperture excitation. The received signal is almost the same when the gap elements is larger than 5.

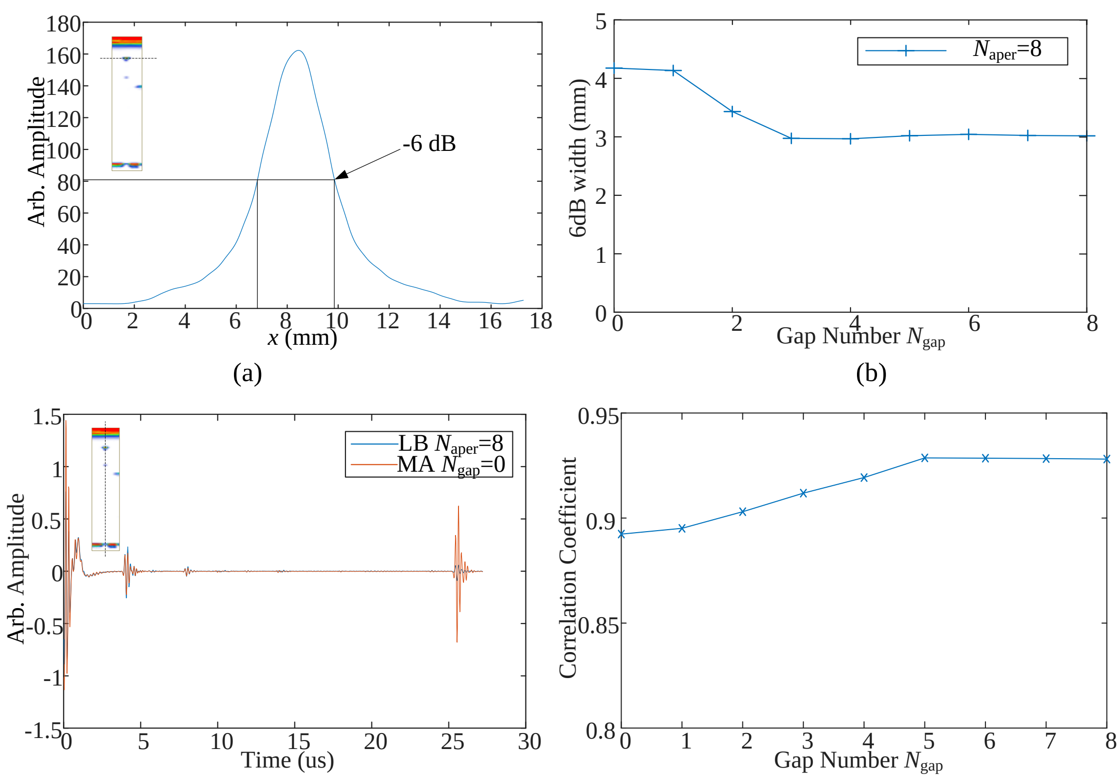


FIGURE 5. Horizontal Cross-section signal of B-scan data of the 3mm side drilled hole (a), -6dB width for the 3mm hole (b), vertical Cross-section signal of B-scan data for linear beamforming and multi-aperture excitation (c) and correlation coefficient with respect to gap number (d)

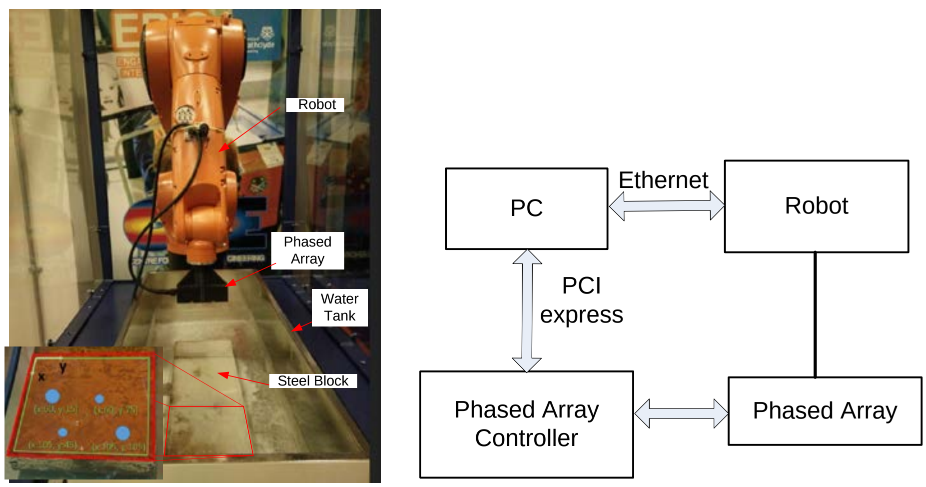
The pulse repetition frequency (PRF) of the phased array controller is 10kHz. For the paintbrush excitation the theoretical frame rate is PRF/N_{pulse} (not considering the data acquisition and streaming time), as all the elements are excited at once. Thus the theoretical frame rate is the same as the PRF. The typical frame rate of different configuration is shown in Table 1. For the robotic inspection using ultrasound phased array, higher frame rate means the robot can move faster, and higher inspection speed is reached.

TABLE 1. Theoretical Frame Rate of the phased array

Type	N_{pulse}	Theoretical Frame Rate (Hz)
Linear Beamforming	25	400
Paintbrush	1	10000
Multi Aperture N_{gap}=0	8	1250
Multi Aperture N_{gap}=6	14	714

AUTOMATED MULTI-APERTURE PHASED ARRAY INSPECTION

An initial test was done with the KUKA KR6 R900 AGILUS robot which can move with speed up to 2m/s, the phased array was attached to the end of the robot arm (Fig.6), a 32-channel phased array system was used to excite the 5MHz phased array. The PCI-express cable was used to transfer the data from FIToolbox to the PC, a 37mm thick steel plate with two 10mm and two 6mm diameter flat bottom holes (10mm and 20mm deep) on the bottom of the steel plate. The steel plate was immersed in a water tank, to guarantee the best coupling during the inspection. The distance between the probe and the upper surface of the steel plate is 20mm.



(a) (b)

FIGURE 6. Automated scan setup using robot and phased array (a), Schematic diagram of the automatic scan system (b)

The raster scan of the steel plate is done with different gaps and pulses, the scan resolution is 1 mm. The robot position information is saved in a text file through Ethernet, while the ultrasound data packets are received and stored into a solid state disk. The ultrasound signals have been encoded through the robot positional feedback through a post-processing MATLAB script, to form a C-scan image [5]. The C-scan result is shown in Fig.7.

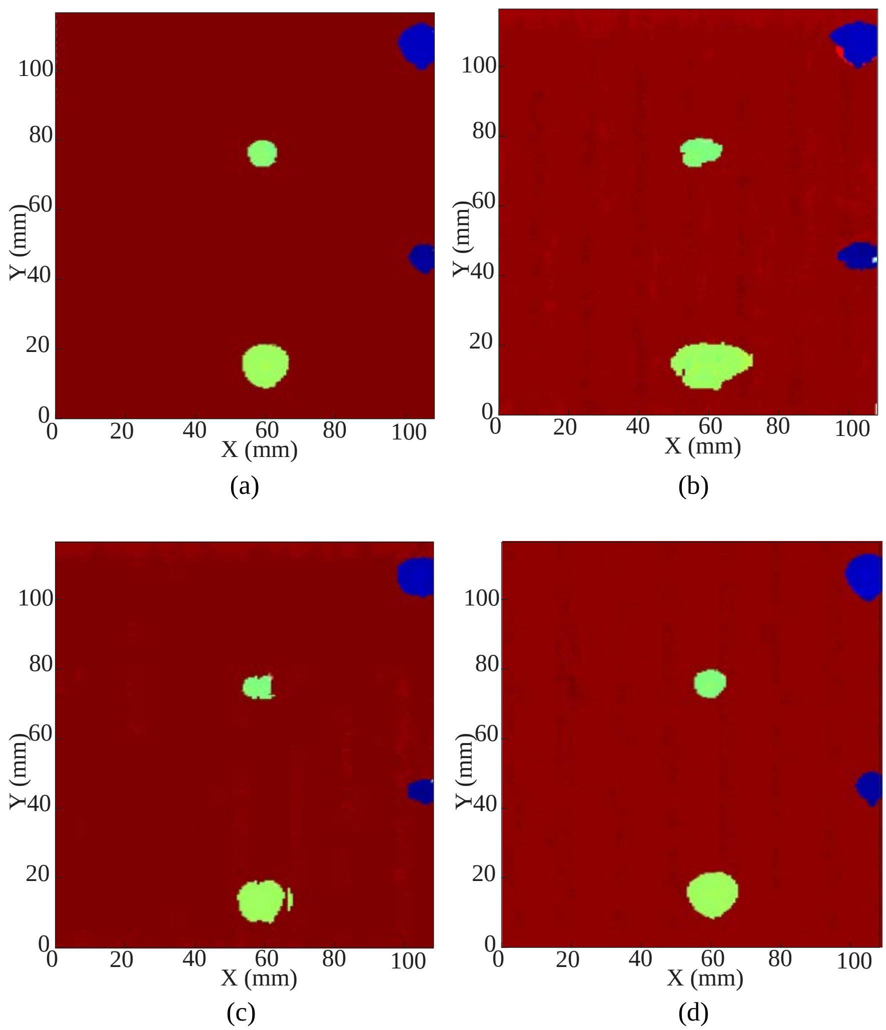


FIGURE 7. C-scan image of the steel block with four flat bottom holes, linear beamforming (a), paintbrush (b), multi-aperture N_{gap}=0 (c), multi-aperture N_{gap}=6 (d)

Figure.7 showed all of configurations are able to detect the four flat bottom holes. The resolution of paintbrush method is the least accurate. For the multi-aperture excitation with zero gap, there is some anomaly around the holes. The multi-aperture excitation with 6 elements gaps produces the same result as linear beamforming. The frame rate of the four setups and the relative maximum scan speed is shown in Table 2. The scan speed of linear beamforming is 660mm/s, but the scan resolution is not good. Optimum resolution can be achieved with traditional beamforming, but it limits the scanning speed to 169mm/s. The scan speed using multi-aperture excitation can go up to 454 mm/s.

TABLE 2. Actual Frame Rate and maximum scan speed of automatic inspection

Type	N_{pulse}	**Actual Frame Rate (Hz)**	**Max Scan Speed (mm/s)**
Linear beamforming	25	169	169
Paintbrush	1	660	660
Multi-aperture N_{gap}=0	8	454	454
Multi-aperture N_{gap}=6	14	286	286

CONCLUSIONS

Multi-aperture beamforming of phased array probes has been developed for fast data acquisition. The performance of the traditional linear beamforming and multi-aperture are compared. With the multi-aperture excitation, the robot scanning speed using phased array can go up to 454 mm/s, compared to 169 mm/s of traditional beamforming. The inspection speed could be further increased if using a 64-channel phased array controller.

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