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Accelerated ultrasonic imaging technique by GPGPU for nondestructive testing of structural concrete components

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ABSTRACT

There is an ultrasonic phased array technique which makes use of scattered longitudinal waves, measured by every two-element combination as a pulser and a receiver, to synthesize high amplitude beams for any points in an inspection area. Using this full-waveforms sampling and processing (FSAP) technique, we demonstrate flaw reconstructions in structural concrete components. To execute the FSAP at high speed, a calculation method with a graphics processing unit (GPU) is introduced. The flaw reconstruction time with a GPU can be dramatically improved compared to that obtained by running the same reconstruction on a computer with CPU only.

1. INTRODUCTION

For ultrasonic nondestructive testing (NDT), we develop a flaw reconstruction technique using a phased array transducer (Nakahata 2012). The technique makes use of scattered longitudinal waves, measured by every two-element combination in the array transducer as a pulser and a receiver. Using this full-waveforms sampling and processing (FSAP) technique, we can synthesize high amplitude beams for any arbitrary angle and/or focal depth with a PC. This approach allows a complete sector-scan reconstruction in an inspection area. However, when we desire flaw shapes with a high resolution, large amounts of floating-point calculation are required for the beam formings. Therefore, computational costs increase especially in the case of three dimensional flaw reconstructions using a matrix array transducer.

Over the past several years, general-purpose computation on graphics processing units (GPUs) is spreading to a wide range of applications (Che 2008). It has been reported that, depending on the application, GPU computing leads to speed-up factors between 5x and 50x on a single GPU versus a single CPU. GPUs significantly outperform CPUs in many fields because the architecture favors the throughput of many parallel threads. Table 1 summarizes the basic performance of NVIDIA's Tesla C2075, which is built for the GPU computing, with 448 thread processor cores per board and high floating-point operations per second (FLOPS). Compared to a CPU, the

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Tesla C2075 supports wide bandwidth for memory accesses, besides the massive hardware multithreading can cover latencies in memory accesses.

In this study, the flaw reconstruction process is accelerated with NVIDIA's GPU and its programming interface, Compute Unified Device Architecture (CUDA) FORTRAN. The speed-up methodology is described and its performance is checked by experimental measurement. Our method is applied to the shape reconstructions of a void in concrete. Concrete material is composed of cement, aggregates, and steel bars for structural reinforcement. Therefore, NDT of concrete is a challenging task because the signal noise (S/N) ratio of flaw echo might be small due to the multiple scattering and the mode conversion among the material (Popovics 2005). To avoid the influence, ultrasonic wave in the low frequency range is used. Since the beam forming by the FSAP can be effective even in the low frequency, the shape reconstruction of an internal slit in concrete is demonstrated in this research.

Table 1 Performance of Tesla C2075 GPU

		Tesla C2075
GPU	Number of SP	448
	Operation clock	1147[MHz]
	Peak performance	1027.7[GFLOPS] (single) 515[GFLOPS] (double)
Memory	Video memory	6[GB] (GDDR5)
	Bandwidth	144[GB/s]

2. FULL-WAVEFORMS SAMPLING AND PROCESSING (FSAP)

2.1 Acceleration of FSAP by GPGPU

The FSAP makes use of scattered longitudinal waves, measured by every two-element combination as a pulser and a receiver, to synthesize high amplitude beams at all pixels of the reconstruction area. The scattered waves are stored in the signal matrix in PC, then focal beams are synthesized by stacking the signals with the delay controlled. Many of commercial phased array systems make focal beams by exciting multiple array elements with adequate delays. Therefore a specific hardware with a delay-circuit is necessary for the beam forming. Nevertheless they can perform beam formings of a few dozen times at most per flaw reconstruction.

In contrast, the FSAP does not need such a delay-circuit. As shown in Fig.1, the transmitting wave is emitted from the *i*-th element, and scattered wave is received at all other element. The received signal is stored as $M_{ij}(t)$ with $j = 1, \cdots, N$ in the signal matrix (*j* = receiving element, *N* = total number of elements). When we repeat this process for all transmitting elements, N*N components are stored in the matrix. We select some signals from the signal matrix, and then stack the signals with time delays controlled. This makes a focal beam for a pixel in the reconstruction area.

From here, we describe how to synthesize the focal beam and reconstruct the flaw. The position $x[k,l]$ represents the pixel location to which we transmit the focal beam. The flight time of ultrasonic wave between the target pixel $x[k,l]$ and the array center represents T_{kl}^{0}. The flight time from the *i*-th element to the *j*-th element by way of $x[k,l]$ can be expressed as $T_{kl}^{0}+\Delta T_{kl}^{ij}$. To obtain a focal beam to $x[k,l]$, we stack the signal $M_{ij}(t)$ by taking the delay ΔT_{kl}^{ij} into account.

$$F(x[k,l],t)=\sum_{i}^{N}\sum_{j}^{N}M_{ij}(t+\Delta t_{ij}^{kl}) \qquad k=1,\cdots,K \qquad l=1,\cdots,\mathrm{L}. \tag{1}$$

In Eq. (1), *K* and *L* are the pixel number in *x* and *y* directions, respectively. After the beam forming, we pick out the amplitude *R* at $t=T_{kl}^{0}$ from Eq. (1),

$$R(x)=F(x[k,l],T_{kl}^{0}) \tag{2}$$

The flaw reconstruction procedure by Eqs. (1) and (2) allows a complete scan with a fine pitch in a target area. If there is flaws at *x*, the amplitude *R* becomes high. Finally, the color map of *R* is output in the PC monitor. In this point of view, our approach is similar to the Sampling Phased Array (Bernus 2006). However, different points from the SPA are that we reconstruct the flaw in the PC memory and introduce fast signal processing such as the band path filtering and the apodization (Olbrish 1997).

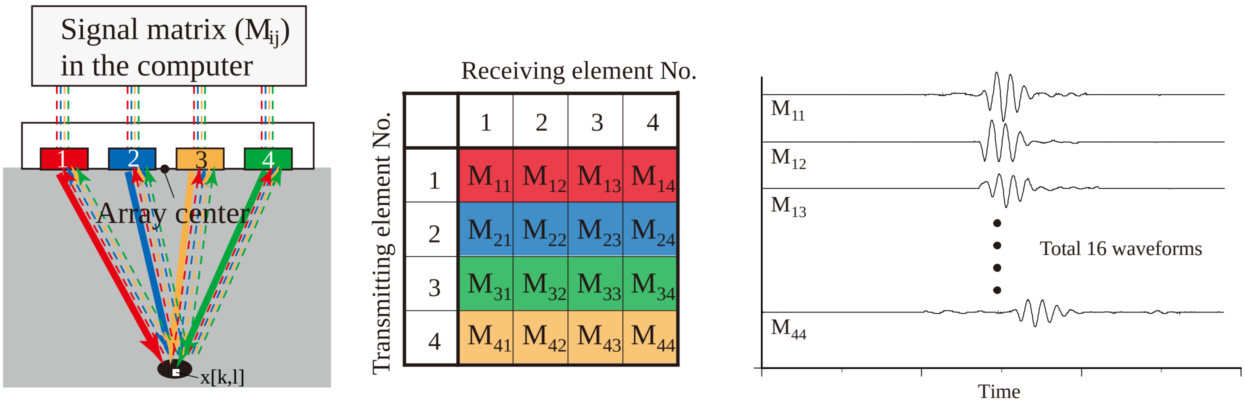

Fig. 1 Basic principle of the full-waveforms sampling and processing (FSAP)

To calculate Eqs.(1) and (2) at high-speed, we introduce a GPU calculation. Recent research on the GPU computing is summarized by (Che 2008), we omit a detailed explanation of the fine grained parallel architecture of NVIDIA GPUs in this paper. Figure 2 shows the calculation process for the shape reconstruction with a GPU. First, all components in the signal matrix $M_{ij}(t)$ are copied from the main memory in the PC to the global memory (GPU memory) as $d\_M_{ij}(t)$. In the FSAP, a signal processing method to extract the scattering amplitude (Schmerr 2007) from received signals is introduced. The method is based on a deconvolution technique, and uses the Fast Fourier Transform (FFT) frequently. Here the NVIDIA CUDA Fast Fourier Transform library (cuFFT) is utilized for the parallel calculation with a GPU. Next, we synthesize focal beams in the reconstruction area. This calculation is executed by CUDA kernels. CUDA organizes a parallel computation using the abstractions of threads, blocks and grids. Here, the CUDA kernel partitions a calculation area to a grid. The grid is divided into blocks and the block is composed by an atomic calculation, a thread. All threads within a block are executed in Single Instruction Multiple Data (SIMD) fashion.

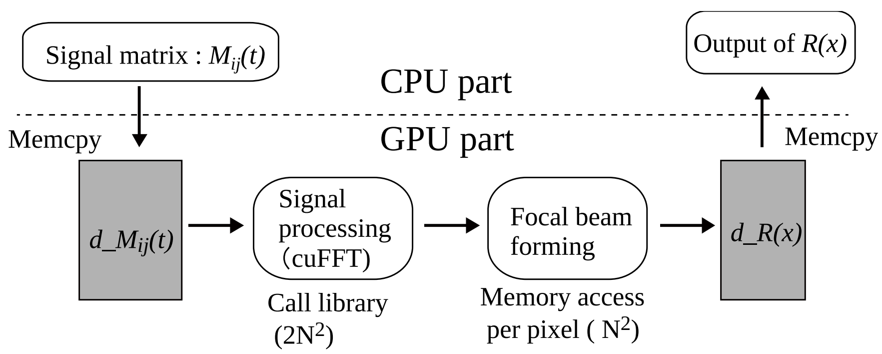

Fig. 2 Calculation process with a GPU computing

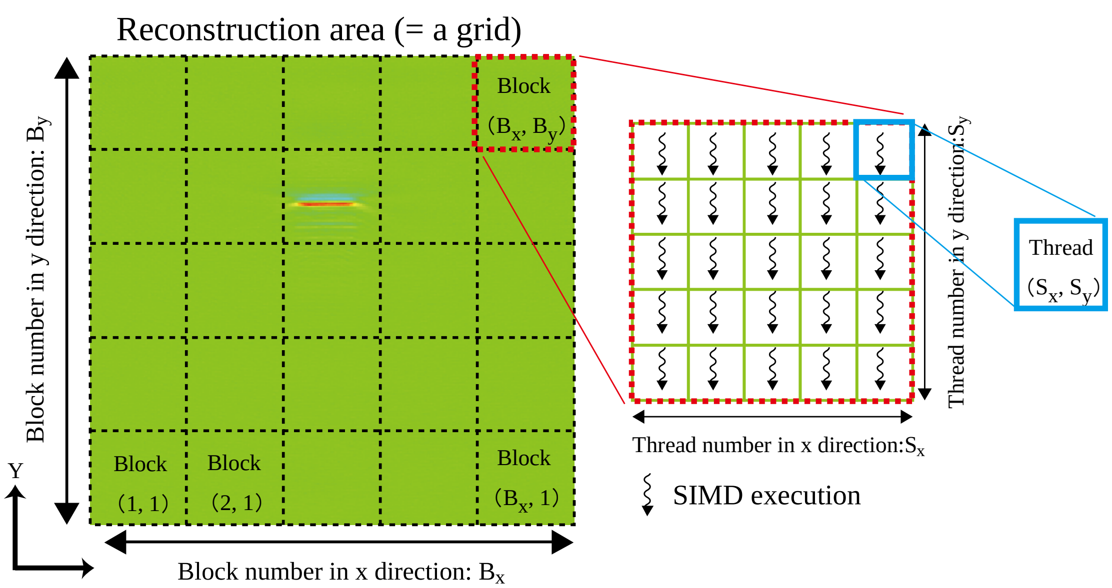

Fig. 3 Hierarchic structure (grid, block and thread) in CUDA and its application to FSAP

Figure 3 shows the block and thread partitions in the process of the focal beam forming. In Fig. 3, a reconstruction area is assigned to a grid. There are B_x x B_y blocks in the grid. In a block, S_x x S_y threads concurrently perform calculations in Eqs. (1) and (2). In CUDA FORTRAN, *gridDim* and *blockDim* refer to the numbers of the grid and the block, respectively. To enhance the parallelization efficiency, fine-granularity threads are required. As shown in Fig. 3, we set *gridDim%x* = B_x, *gridDim%y* = B_y, *blockDim%x* = S_x, and *blockDim%y* = S_y. In our method, the total threads $B_xS_x \times B_yS_y$ are generated in the CUDA kernel. After the beam forming and calculation of amplitude $d\_R(x)$ for all pixel, the data $d\_R(x)$ is transferred to the main memory from the global memory, and then output with a color map.

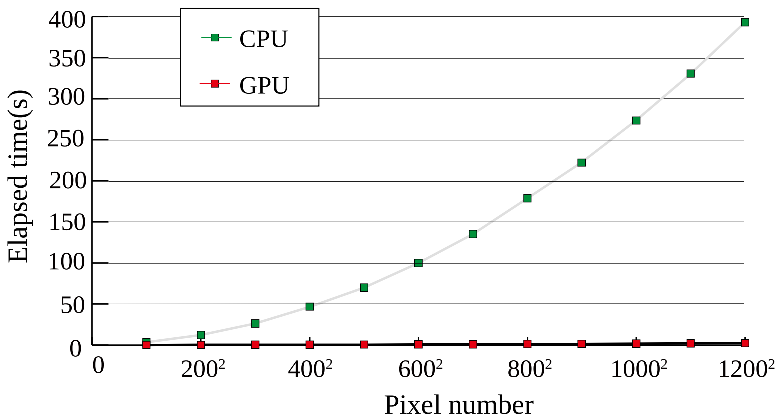

Fig. 4 Calculation time for shape reconstruction including signal processing

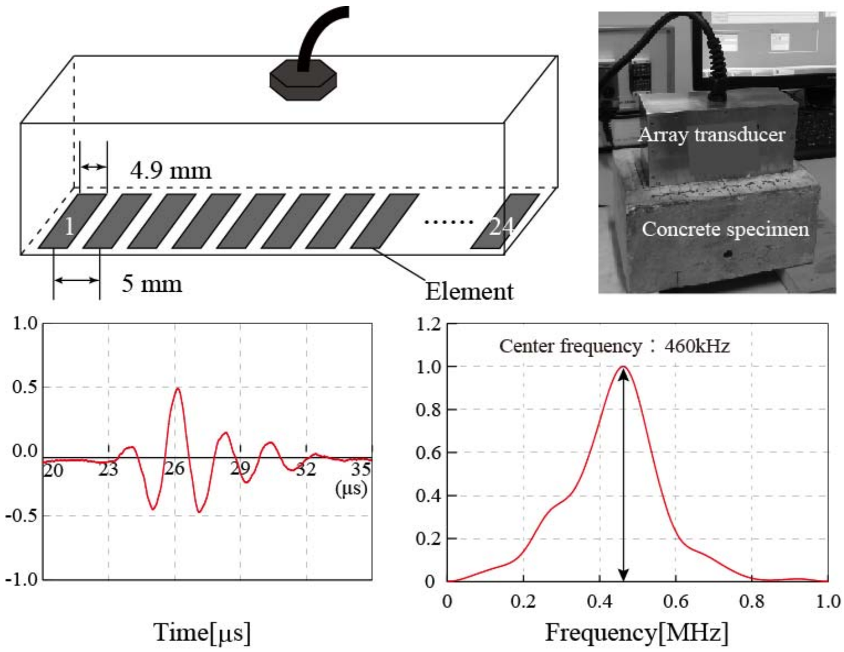

Fig. 5 Dimension of array transducer with 460 kHz peak frequency (upper figure). Reflected signal from the bottom of a metal and its Fourier spectrum (bottom figures).

2.1 Performance Check

To investigate the speed performance of the FSAP, the elapsed time for the shape reconstruction are measured. Figure 4 shows the variations of elapsed time in the case of calculation by CPU and GPU code. Here we choose S_x=16 and S_y=32 for the thread partition. Although the elapsed time by the CPU calculation become large as the pixel number increases, the elapsed time by the GPU calculation are nearly constant. The GPU calculation is approximately 170 times faster than the CPU calculation in the case that the pixel number is 400^2.

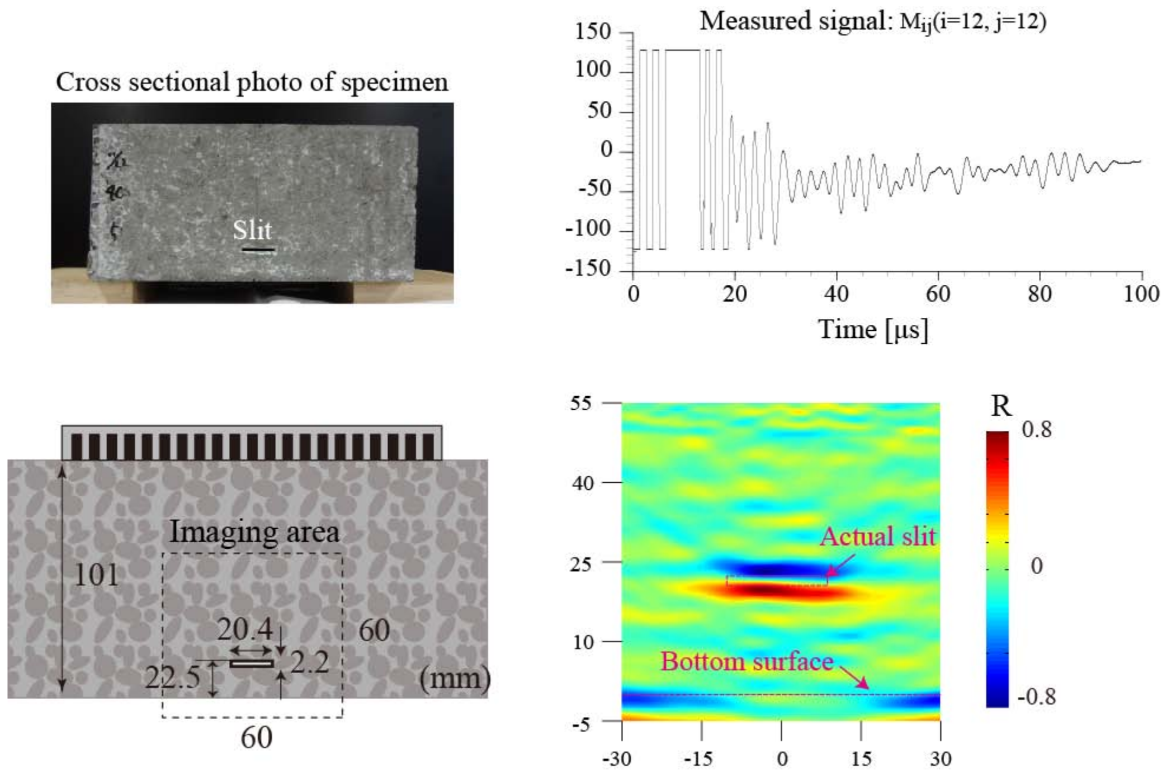

Fig. 6 Shape reconstruction of a slit in concrete specimen with array transducer.

3. SHAPE RECONSTRUCTION OF AN INTERNAL SLIT IN CONCRETE

The flaw reconstruction in concrete specimen is demonstrated using a phased array transducer in the low frequency range. As shown in Fig. 5, the array transducer has total 24 elements, and its element pitch is 5.0mm. The lower figure in Fig.5 shows a reflected signal from the bottom surface of a metal. The signal has 4 cycles and its center frequency is about 460 kHz. Here we make a concrete specimen whose volume fraction of aggregates (the ratio of aggregates to whole volume) is 50%, and the maximum size of the aggregate is 10mm. The ultrasonic wave is transmitted from the array transducer located on the top surface of the specimen, and received in the FSAP fashion. The velocity of the longitudinal wave is 4580 m/s. Here we confirm in advance that the dispersion (Schubert 2001) of ultrasonic wave in concrete is not significant, therefore we use a constant velocity for the shape reconstruction.

As shown in Fig. 6, a slit is drilled on the lower side of the specimen as a flow. The width and thickness of the slit is 20.4mm and 2.2mm, respectively. Here, the reconstruction of this slit is demonstrated. The imaging area is 60 x 60 mm around the slit, and the pixel number is 400^2. From the lower figure in Fig.6, the image of the slit is confirmed, and it is found that a high accurate flaw imaging is possible with the FSAP. The elapsed time for the reconstruction is 0.7 s for this imaging.

4. CONCLUSIONS

In this study, we proposed a high speed ultrasonic imaging method to reconstruct flaws in concrete material. The method is based on the full-waveforms sampling and processing (FSAP) technique, which can synthesize focal beams to any point in a target area. To penetrate ultrasonic wave into a deep part in concrete, ultrasonic wave in the low frequency range is used. The beam forming with the FSAP is possible even in low frequency range by stacking element signals adequately.

Here, the FSAP was accelerated with NVIDIA's GPU and its programming interface, CUDA FORTRAN. The speed-up methodology was described and its performance was checked by experimental measurement. The shape reconstruction of an internal slit in concrete was demonstrated, and it was shown that the accuracy and execution speed of the FSAP are quite good. As a future work, we consider the practical application of our method for actual NDT.

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