Noise Model Implementation in Ultrasonic Velocity Vector Reconstruction with Array Configuration

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Ultrasonic velocity profiler (UVP) is usually used with a single transducer configuration. Array configuration enables two-dimensional or three-dimensional flow mapping. Phased array ultrasonic technique can be utilized to steer ultrasonic beam, which allows wide range scanning even with a smaller transducer. Velocity vector reconstruction technique was developed to estimate two or more-dimensional velocity components while original UVP only obtain one-dimensional velocity component along with an ultrasonic beam. One of the issues regarding the vector reconstruction is the accuracy of the vector. Moreover, there is a mathematical issue. Only two or three 'unknown' velocity components are determined from much larger number of velocity data obtained from multiple array elements. This paper proposes noise model to solve those problems and validates its performance. The design of the array sensor and measurement system are also discussed.

Keywords: Phased array technique, Velocity reconstruction, Noise model

1. Introduction

In March 11th, 2011, the massive earthquake hits north-eastern Japan, which is followed by the devastating tsunami. Then, the nuclear accident at Fukushima Daiichi Nuclear Power Plant of Tokyo Electric Power Company (TEPCO) occurred due to the disaster. TEPCO is currently working on its decommissioning [1]. One of the biggest challenges is the determination of the leakage point of contaminated water from the reactors. High dose rate in the primary containment vessel and reactor building precludes direct human access. Specially developed robots are therefore used to investigate the reactors. Visual investigations are principally accomplished with radiation tolerant camera setups. Stagnant water in the reactors is found to be turbid. Therefore, determination of the leakage point requires other investigation method besides optical observation. Ultrasound measurement is one of the applicable methods. This has also been done before at Three Mile Island-2 in U.S. for determination of the final state of its meltdown core [2].

We have been developing the ultrasonic measurement system for its decommissioning task [3, 4]. Investigation robots suffers size limitation due to the deployment and operation restrictions. Since payload is also restricted, ultrasound measurement system as such is preferably small. Nevertheless, capability of large area measurement is highly requested considering the large space in the reactors. We are proposing the measurement system using the phased array ultrasonic technique to realize those demands. Phased array ultrasonic technique is widely used in non-destructive evaluation (NDE) [5]. Many extensive researches are performed, and advanced measurements are developed and proved, for example, high-resolution imaging technique termed total focusing method. Together with NDE techniques, ultrasonic Doppler method (UVP) can provide valuable insights about the measurement target; NDE technique visualizes objects over the measurement field and UVP depicts flow. There are few literatures of UVP with array sensor configuration [6, 7]. We have been expanding conventional UVP to vector UVP by simultaneous multi-channel signal processing. When an ultrasonic array sensor is designed to realize phased array measurement, ultrasound aperture tends to be relatively small compared to a measurement area. Vector reconstruction relies on the difference of array element positions. Therefore, small aperture compared to measurement area cause vector estimation error. This paper proposes a noise model to solve that. Firstly, specially designed phased array measurement setup is described. Newly proposed signal processing is discussed. Then, performance of the measurement system is evaluated with an experiment.

2. Measurement System

2.1 Cross-Plane Phased Array Sensor

Electric steering is one of the unique features of phased array technique. Multi-channel pulser drives elements in an array sensor with certain time delays. Due to those delays, focused ultrasound beam is formed along beam axis. This focusing can be used to steer ultrasonic beam in different lateral angle. Maximum steering angle is defined by the inter-element pitch and wavelength. Solid body for NDE permits large inter-element pitch compared to liquid media for UVP. For example, steel has a sound speed of approximately 5,900 m/s while water has only that of 1,500 m/s. Therefore, the array sensor design is the key point of the phased array ultrasonic measurement especially for UVP. It is possible to 3D measurements but it is not in the scope of this paper. Ultrasonic array sensor was designed so that maximum beam steering angle of 30 degrees can be formed without significant grading lobe. Basic frequency of 4 MHz was chosen to obtain back-scattered echo from even small particle in turbid water. Each array plane consists of 16 elements since ultrasonic pulser/receiver has a total TRX channel of32. Sound

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pressure is computed with the discrete point source method [8]. After the parametric survey, inter-element is decided to be 0.25 mm. Computed sound pressure for the array sensor is shown in Fig. 1.

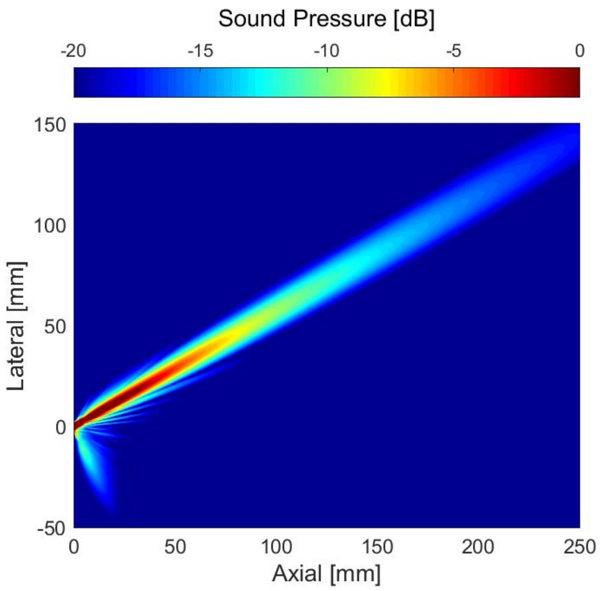

Figure 1: Computed sound pressure with electric steering angle of 30 degrees.

2.2 Pulser/Receiver

Phased array technique requires multi-channel simultaneous ultrasonic excitation. In addition, UVP requires continuous measurement of echo signal in time-series. Pulses are emitted at the predetermined pulse repetition frequency (PRF) and echo signals are sampled with the same interval. In order to realize phased array UVP measurement with larger number of element channels, 32ch pulser/receiver (JAS-21, Japan Probe Co. Ltd.) is custom manufactured (Fig. 2). The pulser/receiver has integrated AD converter and very fast data link to the host computer. Detailed specifications of the pulser/receiver is summarized in Tab. 1. Number of pulse repetitions is implemented using focal law function. Ultrasonic emission and receptions are carried out at certain repetitions. Digitized data is temporally stored on the device memory. After the repetitions, the host device fetches data via USB3 data link and then restart the emission with a command.

Figure 2: Photograph of 32ch pulser/receiver and array sensor.

Table 1: Specification of the 32ch pulser/receiver

TRX Channel	32ch.
Voltage	-300 V (Adjustable, Negative square)
Frequency	10k‑11 MHz (up to 100 cycles)
PRF	up to 1 MHz
Focal Law	up to 4,096
Amplifier	+92dB (TGC)
Analog Filter	LPF, HPF
Digitizer	32 MS/s, 12-bit
Memory Length	8M points/ch.
Data Link	USB3 (max. 400MB/s)

2.3 Software

Each pulse repetition results in a numerous size of echo data sets. Low-level control interface is designed with C++ library to handle data efficiently. The library communicates with a FPGA on the device over the WinUSB driver. The user-side interface was written on NI LabVIEW. State machine is divided into three loops: acquisition, Doppler signal processing and vector reconstruction. Acquisition loop monitors the control settings and communicates with the pulser/receiver via C++ library. Acquired echo data sets are fed to the FIFO. Doppler signal processing loops analyze data on the FIFO sequentially on an independent thread. The analysis algorithm is vectorized and paralleled to improve the performance. Amplitude and quadrature sequence are stored on the data queue. Vector reconstruction loop fetches data from the queue. Moving average filter and algorithm described in section 3 are computed. Results are shown in real-time on the user interface. Snapshot of the program is shown in Fig. 3.

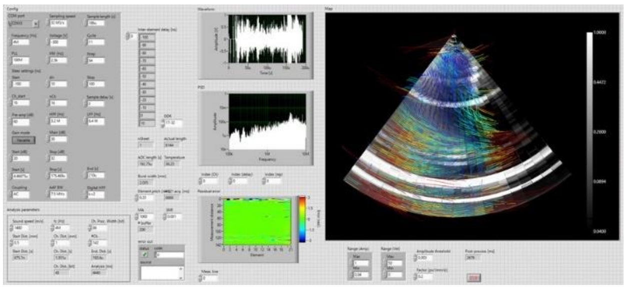

Figure 3: User interface of the measurement software.

3. Vector Reconstruction

3.1 Basic Principle

Fig. 4 illustrates the basic principle of the vector reconstruction for 8 elements configuration. Ultrasonic beam is formed on the designated steering angle with phased array technique. The emission vector is $\boldsymbol{e_e}$. Due to the motion of the reflector particle, reflected echo signal is slightly Doppler shifted. The reception vector varies depending among element channels and Doppler frequency varies as well. Velocity is independently computed for each element at first. Then, those results are combined among N channel as follows.

$$\begin{pmatrix} e'_{1x} & e'_{1y} \\ e'_{2x} & e'_{2y} \\ \vdots & \vdots \\ e'_{Nx} & e'_{Ny} \end{pmatrix} \begin{pmatrix} v_x \\ v_y \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{pmatrix} \tag{1}$$

where reconstruction vector $\overrightarrow{\boldsymbol{e'}}$ is defined as

$$\overrightarrow{\boldsymbol{e'}} \equiv (\overrightarrow{\boldsymbol{e}_\mathrm{T}} + \overrightarrow{\boldsymbol{e}_\mathrm{R}})/2. \tag{2}$$

Previous vector reconstruction was performed along those procedures. However, instantaneous velocity reconstruction was difficult due to vector estimation errors, and time-averaging was required to reduce errors.

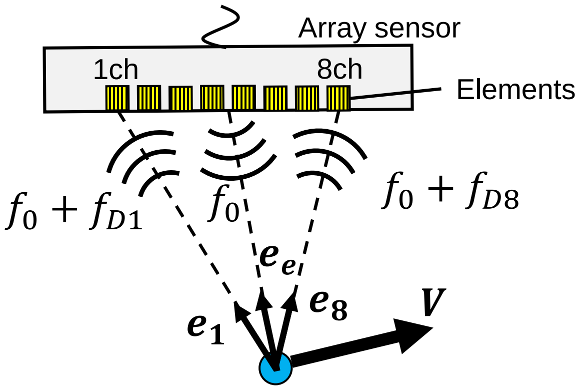

Figure 4: Doppler frequency difference with array configuration.

3.2 Noise Model

As one can see in Eq. (1), the previous reconstruction system was over-determination; only two unknown values are derived from N known values. In order to obtain exact solutions, additional factors shall be introduced. Noise model is proposed to solve this issue. First, define error ratio ER_i as

$$v_i = \overrightarrow{\boldsymbol{e'_i}} \cdot \vec{\boldsymbol{v}} + ER_i. \tag{3}$$

We firstly assumed that fraction of measured data is an error (either plus or minus). This fraction varies in one measurement plane. Second assumption is that error ratio is proportional to the emission and reception directivities D. Total noise level is decided by user-defined SNR.

$$\frac{1}{\mathrm{SNR}} \cdot \vec{\boldsymbol{v}} = \sum \overrightarrow{\boldsymbol{e'_i}} \cdot ER_i \cdot D_T \cdot D_{Ri} \tag{4}$$

Directivity of elements [5] is calculated with inter-element pitch a, basic frequency f_c and sound speed c.

$$D = \mathrm{sinc}\left(\frac{\pi f_\mathrm{c} a}{c}\right) \tag{5}$$

Finally, modified vector reconstruction can be written as follows.

$$\begin{pmatrix} e'_{1x} & e'_{1y} & 1 & \dots & 0 \\ e'_{2x} & e'_{2y} & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ e'_{Nx} & e'_{Ny} & 0 & \dots & 1 \\ -1/D_\mathrm{T} \cdot SNR & 0 & e'_{1x} \cdot D_{\mathrm{R}1} & \dots & e'_{Nx} \cdot D_{\mathrm{R}N} \\ 0 & -1/D_\mathrm{T} \cdot SNR & e'_{1y} \cdot D_{\mathrm{R}1} & \dots & e'_{Ny} \cdot D_{\mathrm{R}N} \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ \mathrm{ER}_1 \\ \mathrm{ER}_2 \\ \vdots \\ \mathrm{ER}_N \end{pmatrix} = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \\ 0 \\ 0 \end{pmatrix} \tag{6}$$

Two velocity components and N errors are estimated by solving this equation (e.g. LU factorization) for each measurement volume.

4. Experiment

4.1 Setup

The experimental setup is illustrated in Fig. 5. The experiment was performed in a tall water tank. The bore diameter of the tank was 580 mm and the height is 1,500 mm. At the bottom of the tank, there is a drain hole of which diameter is 60 mm. Water is slowly drained out at the flow rate of 9 liter/min. Bulk velocity is approximately 50 mm/s.

Cross-plane phased array transducer is installed at the bottom of the tank so that measurement plane covers the drain hole. The sensor surface faced 60 mm behind the edge of the hole. Ultrasonic beam is scanned +/- 36 degrees, which is slightly larger beyond the design discussed in Sec. 2.1. Therefore, results from end beamlines are not reliable. Measurement distance is 140 mm. Pulse is repeated at 2,500 Hz. Measurement time was approximately 540 ms/plane. Velocity profiles are averaged over 200 planes. While two planes are measured during the experiment, only data of vertical plane is discussed here.

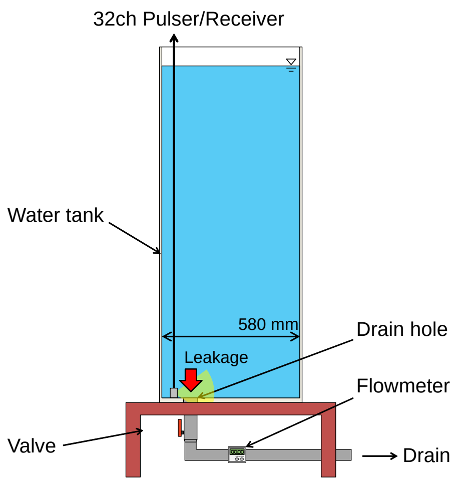

Figure 5: Water drainage observation setup.

4.2 Results and Discussion

Fig. 6 shows comparison of the reconstructed vector maps without and with noise model. Echo amplitude is illustrated in grayscale and velocity vector is color coded (see digital PDF for color). Vector length changes according to the velocity. Three white circumferential zones are observed. Those lines are due to the strong echo reflection from the edges of holes or bottom reflection in the solid wall. Previous reconstruction method causes many erroneous vectors. Since error vector tends to have higher velocity, it is hard to distinguish flow pattern. On the other hand, the map with the noise model successfully eliminates error vectors. Leakage flow can be clearly seen. However, maximum velocity in the drain hole is less than 50 mm/s. It might be associated to inappropriate SNR value used for the reconstruction. Since the purpose of the research itself is to determine the leakage, quantitative velocity measurement was not originally the biggest concern. Yet, for the further investigation, optimized SNR determination will be important.

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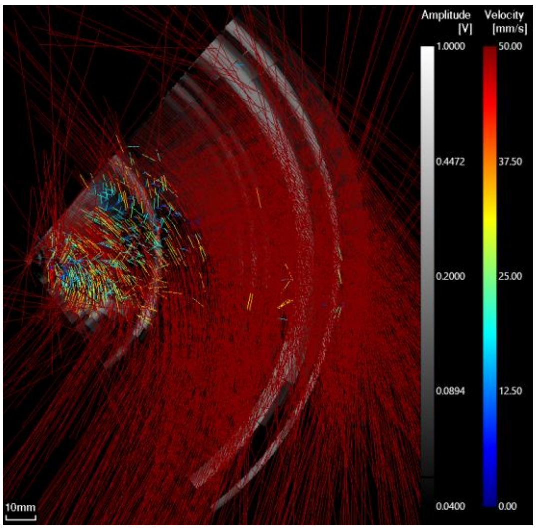
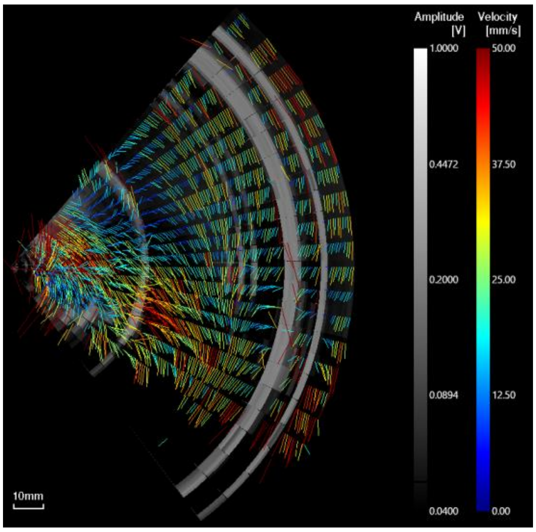


(a)Without noise model.



(b) With noise model.

Figure 6: Comparison of reconstructed velocity vector maps.

5. Summary

Vector map reconstruction is discussed. Phased array technique is used to emit ultrasound in wide angle. Cross-plane phased array sensor is designed using the discrete point source method. Newly developed 32ch pulser/receiver enabled real-time measurement together with specially developed software. Noise model was proposed to mitigate the erroneous velocities in vector reconstruction. The performance of the proposed model is evaluated in the experiment. The flow pattern became clear to identify while the quantitative value deviation is still open for question. Further optimizations of the algorithm and quantitative comparisons will be performed in future work.

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