Development of a Remote Water Leakage Localization System Combined with Phased Array UVP and Robot

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At the Fukushima Dai-ichi Nuclear Power Station (NPS), investigations of NPS condition are conducted to take out fuel debris in order to achieve the decommissioning. However, the primary containment vessels (PCVs) was damaged in the accident and the cooling water injected to cool the fuel debris is leaking out. Therefore, investigating the leakage locations of PCVs is needed to stop leaking. In this research, we developed a system to investigate leakage locations remotely. We applied a flow vector mapping by Phased Array UVP method as a method of investigating leakage locations, and we considered that this method is possible to estimate leakage locations by measuring water flow in the bottom of the PCVs. In order to measure remotely using this method, we have developed a self-localization method. We also have developed a robot which can control sensor positions. After that, we experimented a leakage location estimation by remotely using the developed system, and we confirmed that it is possible to estimate leakage positions from the flow vector map we measured. Therefore, we have developed a basic remote leakage locating system that has the possibility to be applied to investigate the leaking locations.

Keywords: Phased array, Vector UVP, Robot, Remote measurement, Self-localization

1. Introduction

The severe accident at Fukushima Dai-ichi nuclear power station (Fukushima Dai-ichi NPS) occurred due to Tohoku earthquake and tsunami in 2011. At president, Fukushima Dai-ichi NPS has been able to keep stable state while injecting water for cooling fuel debris into primary containment vessels (PCVs), and decommissioning process of Fukushima Dai-ichi NPS is underway [1]. However, because the PCVs have been damaged in the accident, the injected water which is contaminated by debris leaks out from the PCVs. Leakage of contaminated water has become a large problem in taking out fuel debris and proceeding the decommissioning. In order to stop the leakages, detections of these leakages are required. However, because the PCVs are highly-dosed environments, people cannot enter the PCVs and find leakages. Therefore, a remote measurement by robot is required to search for leak locations. Apart from the purpose of identifying the leakage locations, robots have already been inserted for the purpose of investigating the PCVs internal condition. Investigations were conducted by robots which have cameras, and as a result, they are revealed that the existence of fuel debris and the staying water inside of PCV is cloudy. For this reason, optical measurements in a wide range of in-vessel inspection is difficult. Therefore, we focused on the ultrasonic measurement technic for PVCs survey, as this is a measurement method which is possible to meet demands in the environment of PCVs. Because ultrasonic measurement applied measurement for opaque liquid and internal investigation of Three Mile Island nuclear power plant accident, this technique can overcome the environment of PCVs such as a cloudy water and highly-dosed environment. Therefore, we have been developing a technique for identifying leakage locations from flow map using the ultrasonic measurement. For the flow mapping measurement, a phased array vector ultrasonic velocity profiler (UVP) method is proposed by Kikura [2]. The phased array UVP method is a flow measurement method combined with phased array technique which can measure 2-D velocity map of flow in cloudy water. Using this method, we can measure 2-D flow map and it is assumed that the leakage position can be estimated from the flow patterns around leakages.

In order to apply this measurement technology to the investigations in PCVs, it is necessary to consider a method of remotely measuring. Therefore, we aim to develop a remote measurement technology integrating phased array vector UVP method with robot technique. To develop the remote measurement system, we examined the specifications of the robot necessary for identifying leakage locations and furthermore made a basic prototype robot which is composed of a body of four wheels and 3 degrees of freedom robot arm. In addition, we also developed a measurement method to identify the position of the sensor in water. In the self-position identification system, we assumed the estimation of the self-position within a known environment and developed a basic self-position estimation system using particle filter [3]. Then, a verification experiment which measured a flow pattern around mockup leakage were conducted using the developed remote measurement system.

2. Phased array vector UVP

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Phased array vector UVP method is a combination technique of phased array method and UVP method. This measurement method can measure a two-dimensional velocity vector map of flow using only one small sensor. However, the measurable flow is limited to the steady flow at the present time because the time resolution is low due to the necessary of averaging.

2.1 Phased array technique

A picture of ultrasonic phased array sensor and its elements arrangement is shown Fig. 2.1. Phased array sensor has 8 small elements, and the elements are aligned on a straight line in the linear type. By controlling the transmission timing (delay time) independently of each element, generating an arbitrary wave from the principle of Huygens is applicable. By setting the delay time, changing the direction of the ultrasonic beam to provide a steering angle or focus beam is possible. The steering angle θ_s is expressed by the following equation (2.1), where the sound velocity is c, the pitch of elements is d, and the delay time interval between the oscillators is Δt.

$$\theta_s = sin^{-1}\left(\frac{c\Delta t}{d}\right) \qquad (2.1)$$

This steering angle control is one of the major advantages of the phased array method. However, the applicable oblique angle depends on the individual characteristics of sensors and the oblique angle is set within a range in which grating lobes do not occur.

2.2 Phased array vector UVP method

An explanation drawing of the measurement principle of a two-dimensional flow mapping technique using a phased array sensor is shown in Fig. 2.2. It is assumed that the phased array sensor which has eight elements is used in this explanation. Ultrasonic pulses of the center frequency f_0 transmitted from the sensor are reflected at the interface of the tracer particles on the measurement line. After that, the first and eighth elements at both ends receive the Doppler frequencies f_{D1} and f_{D8}. By making simultaneous equations of Doppler frequency and particle velocity equation, the two-dimensional velocity vector V of the tracer particle can be obtained as follows.

$$\boldsymbol{V} = \frac{c}{f_0}\begin{bmatrix}\boldsymbol{e_0} + \boldsymbol{e_1} \\ \boldsymbol{e_0} + \boldsymbol{e_8}\end{bmatrix}^{-1} \cdot \begin{bmatrix} f_{D1} \\ f_{D8}\end{bmatrix} \qquad (2.2)$$

Then, by solving the above equation at each point on the measurement line, it is possible to obtain the velocity vector at a number of measurement points on the measurement line. Furthermore, measuring velocity vector distribution in various directions by changing the transmission direction angle of ultrasonic waves is possible. Therefore, two-dimensional flow mapping can be obtained.

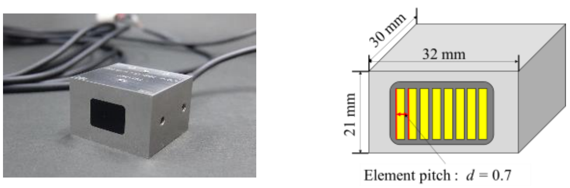


Fig.2.1. Phased array sensor picture and geometry.

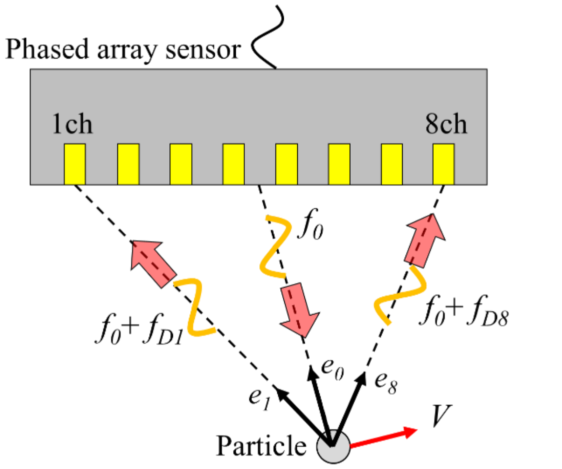


Fig.2.2. The measurement method of phased array vector UVP.

3. Self-locating system

Particle filter is a method of sequentially estimating a state of the system based on the Monte Carlo method. Because the particle filter method can be applied to nonlinear and non-Gaussian state space model, the usefulness of it has been reported in simultaneous localization and mapping (SLAM) method of robotics [4]. In this study, we applied particle filter algorithm to estimate the self-location in the known environment map.

3.1 Particle filter algorithm

Particle filter can be divided into two steps which are prediction step and filtering step. In the prediction step, the state is estimated at time t from the state space model at time t−1. The equation of state estimation at this time is expressed as follows. Note that f represents the prediction model and w_t represents the prediction noise.

$$X_{t|t-1} = f\left(X_{t-1|t-1}\right) + w_t \qquad (3.1)$$

Then, in the filtering step, likelihood calculation is conducted at first. The likelihood is a probability distribution $\mathrm{P}\left(Y_t|X_{t|t-1}\right)$ in which the observation quantity Y_t is observed when the state quantity is $X_{t|t-1}$. Then, resampling is conducted in proportion to the calculated likelihood. Resampling is an operation which delete existing particles numbers of a place where the ratio of likelihood is small and copy other existing particles numbers from a place where the ratio of likelihood is large. While repeating the above prediction step and filtering step, particle filter estimates state on time series data. Then, the estimated value of state is a value with the largest number of particles.

3.2 Self-locating system with particle filter

In self-location estimation underwater, six state quantities (x, y, z, Φ, Θ, Ψ) which considers the three-dimensional coordinate system and the posture angle is required. In this research, we aimed to develop a fundamental system of particle filter, thus the estimated state quantity was limited to two (x, y). For self-location estimation in particle filter, 4 ultrasonic sensors are used. Using these sensors, the distance from the wall surface are measured within the known environmental map and self-location is estimated. In the developed particle filter, uniform linear motion is assumed for the prediction step. In addition, to estimate (x, y), we used (x, y, $\dot{x}$, $\dot{y}$) which added the speed to the state quantity and (v_x, v_y, $v_{\dot{x}}$, $v_{\dot{y}}$) which is prediction noises. Then, the prediction model can be expressed as follows.

$$\begin{pmatrix} x_{t+1} \\ y_{t+1} \\ \dot{x}_{t+1} \\ \dot{y}_{t+1} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_t \\ y_t \\ \dot{x}_t \\ \dot{y}_t \end{pmatrix} + \begin{pmatrix} v_x \\ v_y \\ v_{\dot{x}} \\ v_{\dot{y}} \end{pmatrix} \quad (3.2)$$

In the filtering step, the likelihood calculation assumed a Gaussian distribution for the distance measurements of the sensors. From the positional information D in the water box by the distance measurement of the sensors and the position X^k of the kth particle, the likelihood P^k is obtained as follows. Note that σ^2 is the variance.

$$P^k = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{\left(X^k - D\right)^2}{2\sigma^2} \right) \quad (3.3)$$

3.3 Verification experiment of self-locating system

In order to fundamentally verify the developed self-location estimation system, sensors were controlled position in a water tank which is an internal dimension of 380 × 380 mm by a 3-axis automatic stage and carry out a self-locating experiment in water. Four sensors with a center frequency of 4 MHz manufactured by IMASONIC were used, and four sensors were arranged at a pitch of 90° as shown in Fig. 3.1. The experimental results are shown in Fig. 3.2. In the experiment, the 3-axis automatic stage was applied for position control, the movement was started from the position (250, 90) in the water box. Then, the sensors were moved 200 mm on the Y direction and 145 mm on the X direction, the trajectory became a rectangle. From the result shown in Fig. 3.2, it could be confirmed that the result of the self-location estimation tracked routes almost same with the routes set for the stage. The error between the tracked routes and the route set in the stage was 1.06 mm on average. In addition, the standard deviation was 0.82 and the mode of error was 0.4 mm. Therefore, the certainty of the self-location system was verified.

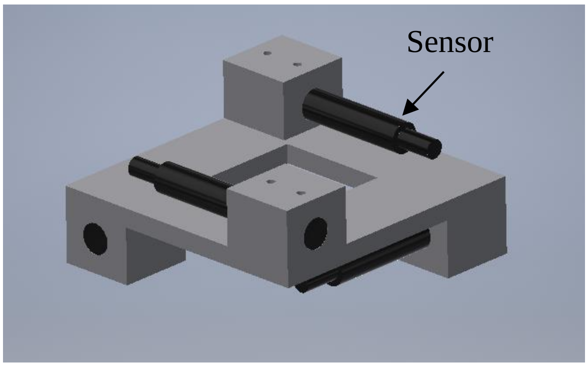


Fig.3.1. Sensor holder for self-locating

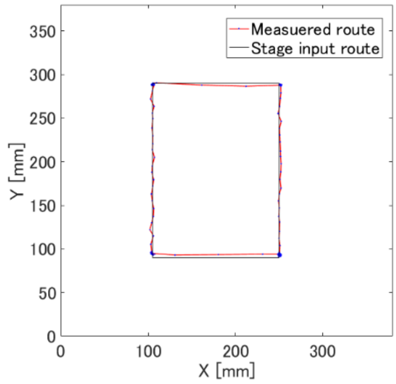


Fig.3.2. Experimental results of self-locating

4. Robot system

In order to conduct the remote measurement, carrying the measurement sensors and controlling the position of them are necessary. Therefore, for a basic remote measurement system, a robot which has four-wheel body with a 3 degree of freedom arm were developed. The picture of the robot system is shown in Fig. 4.1. The robot arm has three-degree-of-freedom using two link mechanism, and the second joint adopts a wire pulley mechanism [5]. The advantage of this robotic arm is lightweight that contributes saving the output of motors. Therefore, the robotic arm is compact and has enough output for transporting phased array sensor. The array sensor was controlled its position by a motor driver (EPOS2 24/5, MAXSON) using a DC motor (RE25 ϕ25 24V 20W, MAXSON). The position of phased array sensor is calculated from the rotary encoder attached to the DC motor. The wheel body robot has EC motor (EC 25 φ 60 24 V 100 W, MAXSON) mounted on each wheels, and independent control is possible by using each motor controller (EPOS2 24/5, MAXSON). Therefore, the mobility of the robot is high and rotating on the spot is possible.

Fig.4.1. Picture of the robot system

5. System Varification and Flow Measurement

We conducted experiments to verify the effectiveness of the remote measurement system developed in a mock-up environment. The outline of the experimental setup is shown in Fig. 5.1. The sensors were carried into a water box by the robot system, and they were controlled their positions near the mock-up leakage location in the water box by the robot arm. After that, self-locating estimation and flow measurement were conducted. The sensors were connected with the robot arm by the sensor holder. At the bottom of the holder, 8ch phased array sensor was attached for flow mapping and 4 other sensors were attached at 150 mm from the bottom for self-location estimatiuon using the holder shown in Fig. 3.1. The phased array sensor applied in the experiemnt has 2 MHz frequency, the elements size are 0.65 × 7.5 mm, and the elements pitch is 0.7 mm. As the environment for mock-up measurement experiment, a mock-up leakage port with an 52 mm inside diameter was made in an acrylic water box which the size is 1200 × 600 × 600 mm and the inner size is 1165 × 550 × 550 mm. Water was circulated at 20 L / min by a magnet pump. Nylon particles which average particle size was 80 µm were mixed in the water as tracer particles. The measurement line of the ultrasonic beam was controlled from -10° to 10° at intervals of 5°, hence five measurement lines were scanned. The flow velocity distribution was measured and averaged 1000 times on each measurement line.

In the experiment, the flow pattern close ot the leak port was measured. We planned to place the sensors in order of measurement points A, B and C as shown in Fig. 5.2.

The measurement results are shown in Fig. 5.3. By self-locating system using particle filter, position informations of points A (229.9, 105.5), B (272.9, 99.0) and C (324.9, 101.9) were measured. Moreover, the flow pattern can be confirmed flow toward to the leakage location from the measured flow map, especially the strongest flow can be confirmed at measurement point B where the position was in front of the leak port. In the measurement of point B, the flow from the positive direction of the X-axis is more strongly measured. However, this is considered to be due to the position of the inlet port. From the results, the effectiveness of the remote measurement system was confirmed.

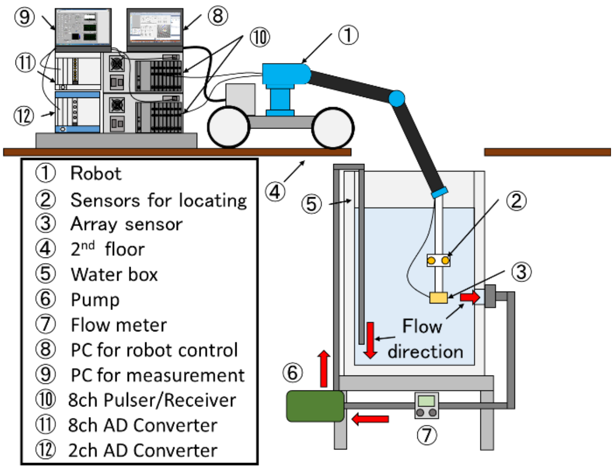
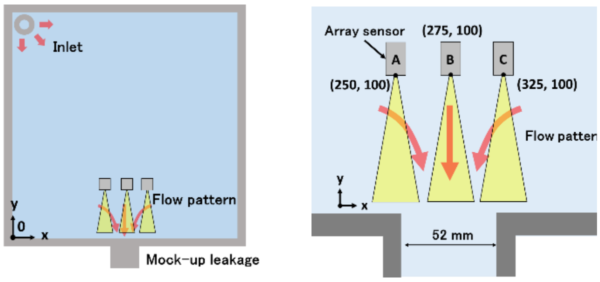


Fig.5.1 Setup of measuring flow field around mock-up leakage



(a) Top view (b) Near the leak port

Fig.5.2. Measurement points in the water box

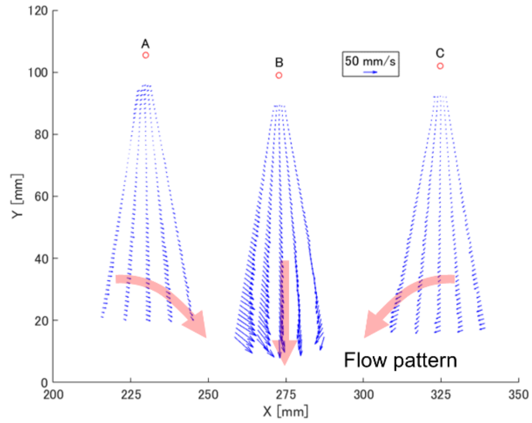


Fig.5.3. Measurement results of self-locating and flow mapping

6. Conclusion

In this research, the basic development of the remote measurement system for investigating the PCVs leakage locations of the Fukushima Daiichi Nuclear Power Station was conducted. We developed a remote measurement system by integrating the robot and the measurement system which is consist the self-position estimation system and Phased array vector UVP method. Then, we conducted 2D-flow field measurement near the leak port in mock-up environment using the developed system. From the experimental results, we could confirm the effectiveness of the system.

References

[1]Ministry of Economy, Trade and Industry of Japan: TEPCO Medium and long term road map for decommissioning of Fukushima Daiichi Nuclear Power Station http://www.meti.go.jp/earthquake/nuclear/pdf/20171003.pdf, (in Japanese), (2017).

[2] H. Kikura, et al.: Study on Ultrasonic Measurement for Determination of Leakage from Reactor Vessel and Debris Inspection, The 11th National Conference on Nuclear Science and Technology, Da Nang, (2015).

[3] G. Kitagawa: Monte Carlo filter and smoother for non-Gaussian nonlinear state space models. Journal of computational and graphical statistics, 5(1), (1996), 1-25.

[4] F. Dellaert, et al. Monte Carlo localization for mobile robots. 1999 IEEE International Conference on Robotics and Automation, Detroit, (1999).

[5] S. Hirose, et al: Development of Tendon Driven Multi-Joint Manipulator Based on Coupled Drive, The Society of Instrument and Control Engineers, 26(11), (1990), 1291-1298.