Development of Under Sodium Viewer for Next Generation Sodium-cooled Fast Reactors

K. Aizawa[1], Y. Chikazawa[1], K. Ara[1]

M. Yui[2], Y. Uemoto[2], M. Kurokawa[2], T. Hiramatsu[3]

[1]Japan Atomic Energy Agency (JAEA), 4002 Narita, Oarai, Ibaraki 311-1393, Japan

Email contact of main author:aizawa.kosuke@jaea.go.jp

[2]Mitsubishi Heavy Industries, Ltd., 1-1-1 Wadamisaki, Kobe, Hyogo 652-8585, Japan

[3]Mitsubishi FBR Systems, Inc., 2-34-17 Jingumae, Shibuya, Tokyo 150-0001, Japan

Abstract. Inspection in opaque liquid metal coolant is one of important issues for sodium-cooled fast reactors. To facilitate operations and maintenance activities, various under sodium viewers (USVs), including horizontal USVs for obstacle detection for a long distance and imaging USVs for a short and middle distance imaging, have been developed in several research institutes and countries. In this study, an imaging USV for a middle distance, approximately 1 m, has been developed. The USV in this study adopts an optical receiving system which measures the vibration displacement of diaphragm by using a laser as a receiving sensor. This study mainly focuses on the sensitivity improvement for a transmission sensor and the receiving sensor. In addition, an imaging experiment in the water was conducted using the new transmission sensor and receiving sensor. The experimental results showed that the newly developed USV sensors can make higher resolution images of a target than the previous sensors.

Key Words: Sodium-cooled fast reactors, USV, Sensitivity improvement

1. Introduction

Inspection in opaque liquid metal coolant is one of important issues for sodium-cooled fast reactors. To facilitate operations and maintenance activities, various under sodium viewers (USV), such as horizontal USVs for obstacle detection for a long distance and imaging USVs for a short and middle distance imaging, have been developed in several research institutes and countries. For example, JAEA developed a horizontal USV and demonstrated it in Monju [1]. The experimental results confirmed the basic performance of the horizontal USV for obstacle detection in between the core and the upper core structure. Pacific Northwest National Laboratory (PNNL) developed an imaging USV system, which is directly installed with the transducer in liquid metal [2, 3], and investigated materials and bonding methods for in-between the transducer and transducer face plate. Argonne National Laboratory (ANL) developed an imaging USV system that uses the waveguide transducer [4, 5], which, on the contrary, is not directly installed in liquid sodium; it catches the ultrasonic signal with the waveguide installed in liquid sodium instead. The ANL's imaging USV demonstrated its performance for a short distance between the transducer and measurement place. In France, an imaging USV system, for a short distance, equipped with a transducer in liquid metal was developed and demonstrated in Phenix [6, 7]. Toshiba Corporation developed an imaging USV for a middle distance (1 m) [8].

In this study, an imaging USV for a middle distance, approximately 1 m, has been developed.

The USV in this study adopts an optical receiving system which measures the vibration displacement of diaphragm by using a laser as a receiving sensor. This study mainly focuses on the sensitivity improvement of the transmission sensor and the receiving sensor. An imaging experiment in the water was conducted by using a newly improved transmission sensor and receiving sensor.

2. Development Requirement

Table I shows requirements for the USV system in this study and for a previously developed USV by JAEA [9, 10]. As described in the chapter 1, the distance from the device to the target is approximately 1 meter. The target resolution is equivalent to the VT-3 [11], and is specifically set to image a deformation of instrument, looseness of bolt, and loss of instrument. The USV system will be operated during a regular inspection time which strongly depends on the power costs. Therefore, the target measurement duration should be as short as possible to eliminate the effects on the duration of regular inspection. The future target is to conduct a real-time imaging.

TABLE I: REQUIREMENTS FOR THE USV SYSTEM DEVELOPMENT.

	Present study	Previous study [9, 10]	Remarks (This study)
Distance from device to the target [m]	Approximately 1.0	Approximately 0.1	
Target resolution	Equivalent to VT-3	Identification of external crack (interim target 0.3 mm)	Deformation of instrument, looseness of bolt, loss of instrument
Target measurement duration	As short as possible	No requirement	Reduction of measurement time to eliminate the effects on regular inspection time

3. Development Plan

The USV system consists of a transmission sensor, a receiving sensor, and an optical processing system as shown in Figure 1. The USV adopts the optical receiving system which measures the vibration displacement of diaphragm by using a laser as a receiving sensor.

The system needs to perform for a longer distance (approx. 1 m) than the previous study, between the device and a target and to reduce measurement time. It is important to reduce the dependence on the signal processing, for example the averaging procedure, to shorten the measurement time. This study mainly focuses on the two tasks for these development requirements. One is to increase the signal intensity in the transmission sensor, the other is to improve the wave profile by increasing the damping performance in the transmission sensor and reducing noise in the receiving sensor.

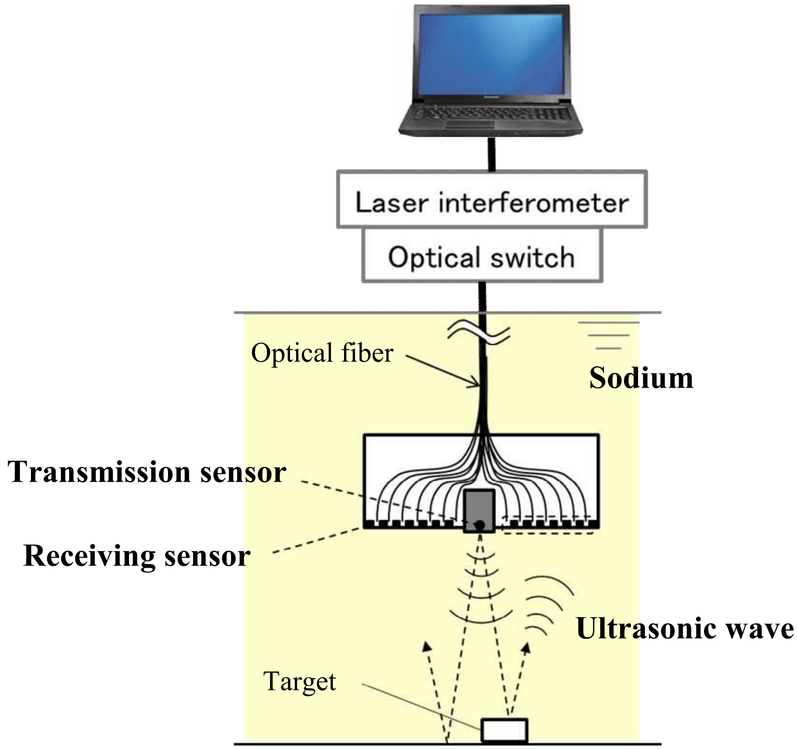


FIG. 1. Composition of USV

4. Development of Transmission Sensor

Table II compares main specifications of the piezo element in the transmission sensor in this study, which meets the requirements, and the one used for the JAEA's previous USV. Ultrasonic wave has characteristics that its higher frequency increases the theoretical resolution, however, it tends to decreases the signal intensity. This study's target resolution is a few mm and lower compared to the previous study, it therefore allowed the frequency to be lowered down to 2 MHz to prevent the decrease of the signal intensity. Accordingly, the piezo element was thickened to 1 mm and thicker because the thickness depends on the frequency. In addition, the diameter of the piezo element was enlarged to 20 mm and larger to increase the signal intensity since the approach distance in this study is longer than the previous study; as a result, the directivity angle of the piezo element decreased due to the increase in size.

The transmission sensor consists mainly of the piezo element, a damper and a diaphragm as shown in Figure 2. The piezo element vibrates by applying a voltage. This vibration changes sound pressure and propagates in sodium. The USV system operates in 200-degrees C sodium, however the piezo element is not heat resistant. The piezo element hence is covered with the diaphragm. The damper is installed inside the sensor to reduce the echo signal. The damping performance and the loss reduction in the joint of the piezo element and the diaphragm are important to increase the signal intensity and improve the wave profile. This study has investigated the fabrication method and the design suitable for the piezo element. The new transmission sensor was fabricated based on the investigation results.

TABLE II: MAIN SPECIFICATIONS OF A PIEZO ELEMENT IN THE TRANSMISSION SENSOR ADAPTED TO THE DEVELOPMENT REQUIREMENTS.

	This study	Previous study
Demand for resolution (1)	Medium (a few mm)	High (approx. 0.3 mm)
Frequency of ultrasonic wave	Low (2 MHz)	High
Thickness of piezo element	Thick (1 mm)	Thin
Demand for approach distance (2)	Long (1 m)	Short (0.1 m)
Diameter of piezo element	Large (20 mm)	Small
Directivity angle of ultrasonic wave	Narrow	Wide

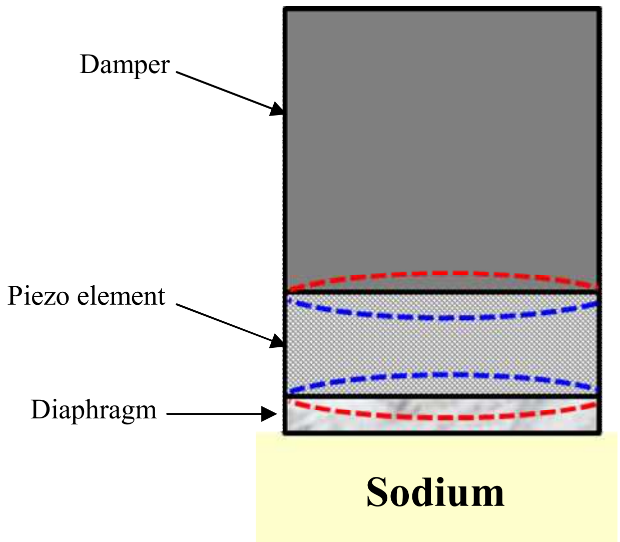


FIG. 2. Composition of transmission sensor

Figure 3 compares the sound pressure distributions of the new and the previous sensors obtained in water experiments. The distance from the transmission sensor to the receiving sensor is 1 m. The same receiving sensor was used in the both cases. The horizontal axis shows the radial distance from the center of the piezo element, while the vertical axis represents sound pressure normalized by the sound pressure at the center of the previous sensor. As shown in the figure, the new sensor achieved 20 times higher sound pressure than the previous one on the wide range.
Figure 4 shows the wave profiles of the new and previous sensors. The number of waves detected by the new sensor is four, which is fewer than that of the previous one.
These results revealed that the new transmission sensor has better sensitivity.

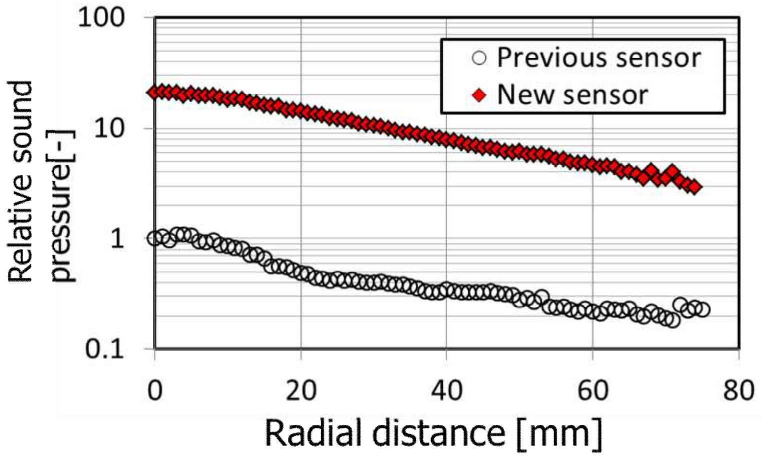
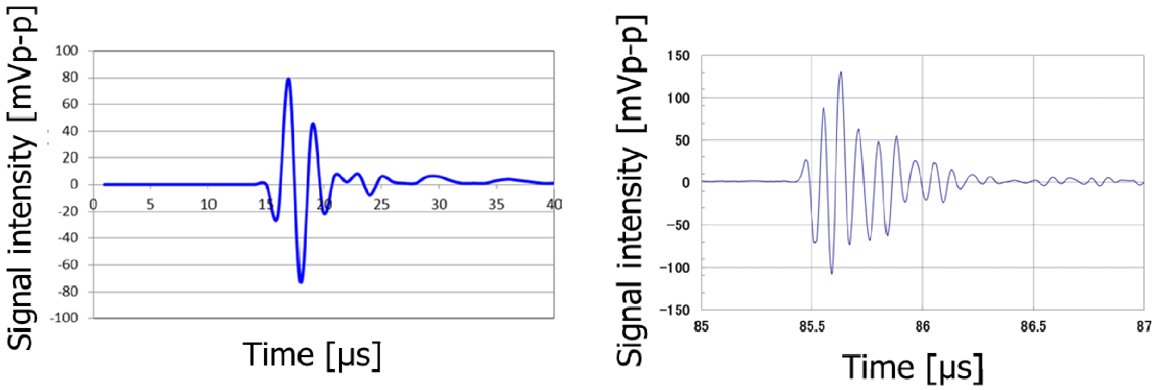


FIG. 3. Sound pressure distribution in 1 m distance (Water experiment)



(a) New sensor (b) Previous sensor

FIG. 4. Wave profile of transmission sensor

5. Development of Receiving Sensor

The receiving sensor consists mainly of the diaphragm, a sensor body, and optical fibers as shown in Figure 5. The vibration displacement of diaphragm on its receiving surface is measured by using a laser. The ultrasonic wave propagation in the sensor body leads to the degradation of ultrasonic wave profile. Constant vibrations on each receiving surface are required to obtain an image with higher resolution. This study adopted the sound isolation function between the diaphragm and the sensor body to reduce the ultrasonic wave propagation in the sensor body. This study has investigated the relation between the diameter and thickness of diaphragm and the receiving sensitivity to optimize the receiving surface shape, and found out a suitable fabrication method for the receiving sensor to obtain the constant vibration in each receiving surface.
Figure 6 shows the wave profiles of the new and the previous receiving sensors. The new sensor has successfully reduced the noise of the wave profile.

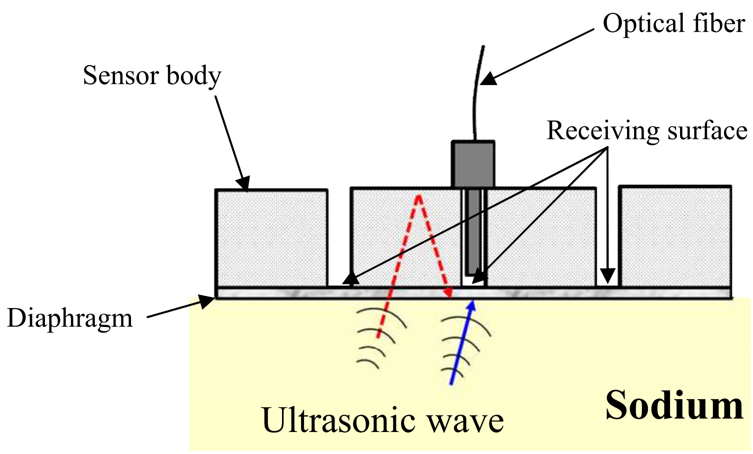
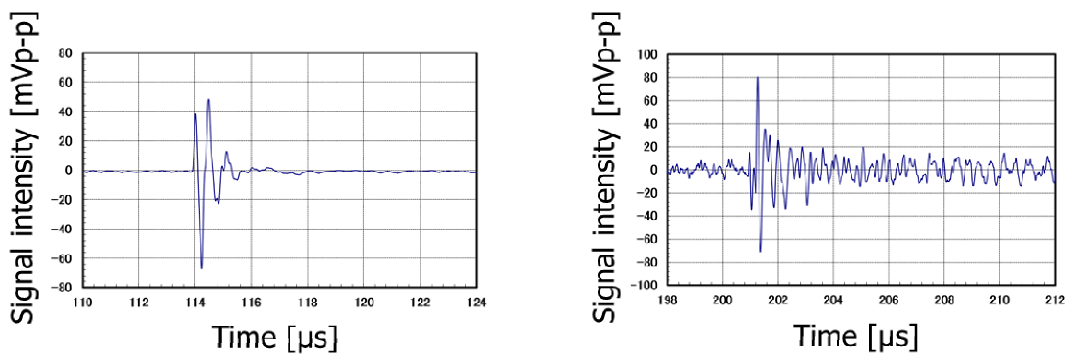


FIG. 5. Composition of receiving sensor



(a) New sensor (b) Previous sensor

FIG. 6. Wave profile of receiving sensor

6. Imaging Experiment

An optical photograph of imaging targets taken by the new transmission sensor and receiving sensor at the imaging experiment is shown in Figure 7. The targets are lines and spirals. The horizontal and axial visibility was evaluated based on the appearance of the line and the spiral targets, respectively.

Table III shows the experimental conditions along with details of the imaging targets. The width of the each line is 3 mm, and the distances between them are 3 mm, 5 mm, and 10 mm. The spiral target has 2-mm distance (in height) between each thread. The distance from the transmission sensor and the receiving sensor to the target is approximately 800 mm. The transmission sensor performed at the same position. On the other hand, the receiving sensor moved around the 300 mm square from the target center to receive the ultrasonic wave reflected from the target. The synthetic aperture focusing technique was adopted because this is an efficient and appropriate method to compute images in terms of the horizontal resolution for a long-distance imaging.

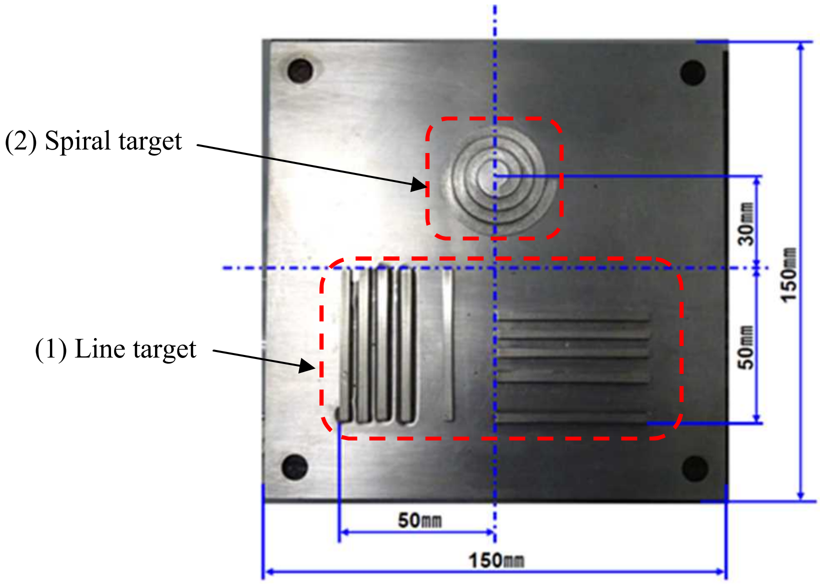


FIG. 7. Photograph of imaging target

TABLE III: EXPERIMENTAL CONDITIONS.

Item	Condition
Sensor	New transmission sensor, New receiving sensor
Medium	Water
Target	(1) Line target Line width: 3 mm Line length: 50 mm Distance between lines: 3mm, 5mm, 10mm (2) Spiral target Distance between the threads: 2 mm Line width: 4mm
Distance from the sensor to the target	Approximately 800 mm
Receiving range	300 mm square, 4 mm pitch
Imaging computation method	Synthetic aperture focusing technique

Figure 8 shows a synthesized image of the overall target. The dotted line in the figure represents the visualization range captured by the new transmission sensor in the water experiment, which is about 120 mm in diameter, from 800 mm distance. As shown in the figure, visualization of the each line target was achieved. Therefore, the horizontal resolution obtained by the new USV sensors is less than 3 mm from 800 mm distance.

Figure 9 shows the synthesized images of the spiral target, in which the sliced images and the side views are pictured. As shown in the sliced images, each thread of the spiral target can be clearly recognized. By using the synthesized images, the distance of the thread was evaluated as 1.9 mm; the actual distance is 2 mm. Therefore, the axial resolution obtained by the new USV sensors is less than 1 mm from 800 mm distance.

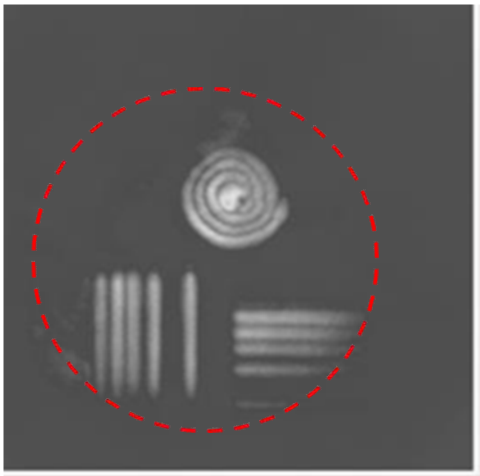


FIG. 8. Synthesized image

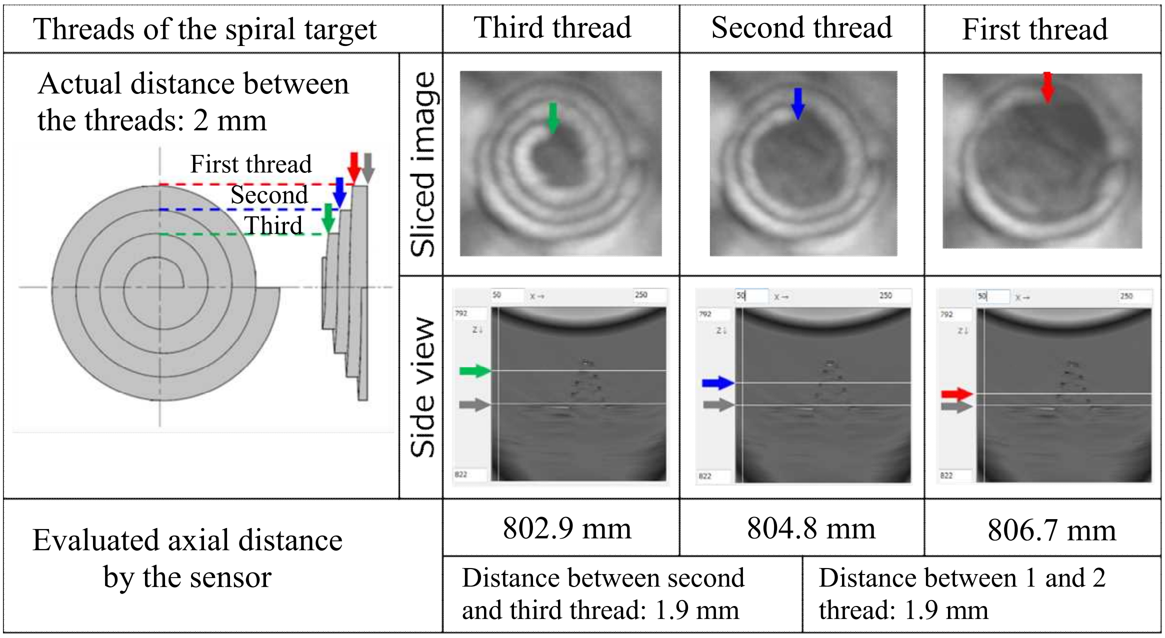


FIG. 9. Synthesized image of the spiral target

7. Conclusion

This study has developed an imaging USV for a middle distance, approximately 1 m, mainly focusing on the sensitivity improvement of a transmission sensor and a receiving sensor compared to the previous sensors. The new transmission sensor has achieved 20 times higher sound pressure and improved the imaging of the wave profile. In addition, the new receiving sensor successfully reduced the noise of the wave profile. The results obtained through the imaging experiment in the water showed that the new USV sensors can make images with higher resolution from 800 mm distance. The horizontal resolution is less than 3 mm, while the axial resolution is less than 1 mm.

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