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A Non-Contact Ultrasonic Sensor for Pipe-Wall Thinning Inspection of Nuclear Power Plants

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ABSTRACT. Aiming to reduce inspection time of a pipe-wall thinning measurement in a nuclear power plant, we have been developing a non-contact ultrasonic sensor which was originally proposed by University of Bristol. In this study, sensor durability against temperature cycles and irradiation which needs to be confirmed to introduce the sensor into actual plant inspection has been experimentally investigated. The experiment results have shown that the sensor has sufficient durability against both in the nuclear power plant condition. In addition to this, we have proposed multi-transducer system where multiple transducers are connected to one transducer coil for further reduction in the inspection time. A prototype of this concept has been manufactured and its feasibility has been experimentally confirmed.

INTRODUCTION

Piping systems, such as within an oil and gas system, a chemical plant, a fossil-fuel plant, a nuclear power plant and so on, are subject to corrosion and/or erosion which cause thinning of the pipe wall. Nuclear power plants have experience some incidents due to the pipe-wall thinning. Representative ones are at the Surry Unit 2 in 1986 [1] and at the Mihima Unit 3 in 2004 [2]. Following these incidents, a number of research programs were conducted [3-8], and then ultrasonic thickness measurements are now commonly used for inspection of the pipe-wall thinning in the nuclear power plants. In Japan, numerous ultrasonic thickness measurements are manually carried out during the outage of a nuclear power plant. Most of the pipes in the nuclear power plant are covered with insulators, so the insulator must be removed before the ultrasonic measurement. Since the supplemental works, such as the insulator removal, are known as time-consuming processes, the inspection technology which enables the pipe-wall thickness measurement without the insulator removal is desirable to reduce the inspection time of the pipe-wall thickness measurement.

Zhong et al. from University of Bristol [9] proposed an innovative sensing technology based on electromagnetic induction between coils. Since pulser/receiver and a transducer can be inductively coupled in this technology, no cable is required between them. This means that the sensor has a capability to perform the pipe-wall thickness measurement without removing the insulator if the coils can be inductively connected through the pipe insulator. To confirm applicability of this technology (called a non-contact ultrasonic sensor in this paper) to the actual plant inspection, a feasibility study was performed in the previous research [10]. Measurement accuracy, maximum offset between coils and effect of the insulator on the inductive coupling were investigated. One of the remaining confirmation items is durability against temperature cycles and irradiation. In this study, we experimentally investigate the sensor durability against temperature cycles and irradiation. Also, aiming further reduction of the inspection time, we propose new concept of the non-contact ultrasonic sensor.

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A NON-CONTACT ULTRASONIC SENSOR

Basic Concept and Application to Pipe-Wall Thinning Measurement

Figure1 illustrates the non-contact ultrasonic sensor proposed by Zhong et al [9]. It consists of two parts: a sensor and an inspection rod. The sensor is attached on the surface of the inspection target. The sensor has a sensor coil and a transducer, which are connected with each other. The inspection rod contains a transmitter coil and a receiver coil. As shown in Fig. 1, there is no cable between the inspection rod and the sensor because they are inductively coupled by the coils. The right of Fig. 1 shows application of the non-contact ultrasonic sensor to the pipe-wall thinning measurement of the actual nuclear power plant. Firstly, the sensors are bonded to the pipe surface with high temperature adhesive because the temperature of the pipe becomes around 200 deg C. Then the pipe is covered with the insulator as shown in Fig. 1. Once installation of the sensor and the insulator is completed, the ultrasonic measurement without removing the insulator can be available. Other inspection methods (e.g. pulse eddy current [11]) provides the thickness measurement without the insulator removal as well, but the accuracy unfortunately becomes lower than that of the manual ultrasonic measurement. On the other hand, the non-contact ultrasonic sensor can achieve the same accuracy because its measurement principal is identical to that of the manual ultrasonic measurement except for data transfer due to the electromagnetic induction.

In the previous study [10], the measurement accuracy, maximum offset between the coils and effect of the insulator on the inductive coupling were confirmed. In the following sections, the sensor durability against temperature cycles and irradiation is experimentally investigated.

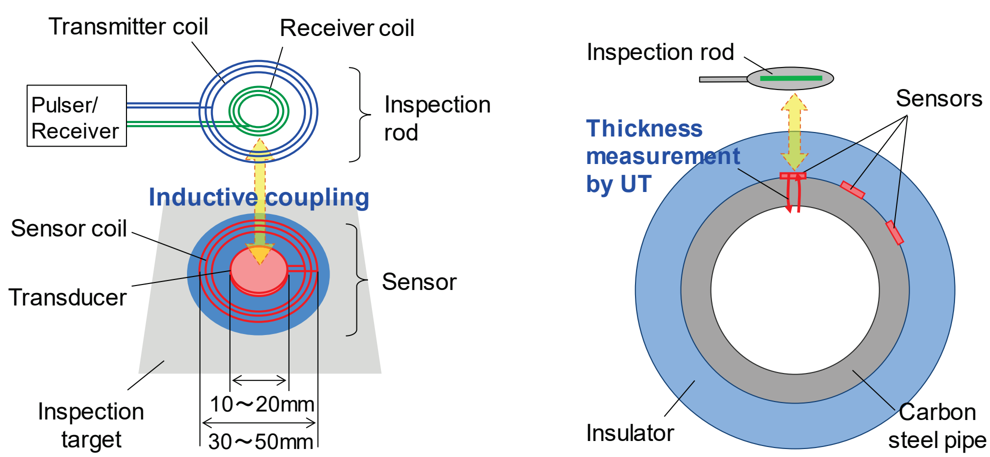
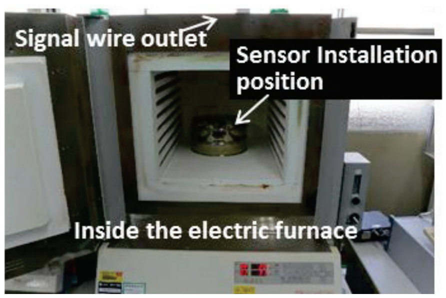


FIGURE 1. Concept of the non-contact ultrasonic sensor and application to the pipe-wall thinning measurement (right figure).

Temperature Cycle Test

As described above, the sensors are bonded to the pipe surface and are left there. This means that the sensors will be revealed to high temperature and radiation environment. In terms of temperature durability, the temperature cycle due to the outage of the plant could be the most severe condition because thermal expansion of the transducer is quite different from that of the inspection target. In order to confirm the temperature durability of the sensor, we performed temperature cycle tests by using a test apparatus and test condition shown in Fig. 2. The sensor was attached to the carbon steel specimen with the high temperature adhesive. In these tests, the temperature was changed from 20 to 200 deg C with the ramp speed of 1 deg C/min which is faster than that of the actual plant restarting from the outage. The maximum temperature was chosen from the representative temperature of feedwater line in the boiling water reactor. The number of temperature cycles (from 20 to 200 deg C) was set to 40, considering the nuclear power plant life in Japan. It should be noted that retention time at maximum temperature in these tests is only 24 hours. This is quite shorter than operation period of the nuclear power plant. Thus, the sensor durability against a long-term high temperature condition needs to be confirmed in the future study.

The wave forms and the signal amplitude variation during these tests are shown in Fig. 3. Since all data were acquired at the room temperature, there are no velocity change due to temperature variation. Regardless of 40 times temperature cycles, the wave forms were almost identical and no degradation of the signal amplitude was observed in these test conditions. The further investigation regarding the temperature durability will be performed in the future study.



Temperature	20 - 200 deg C
Ramp speed	1 deg C/min
Retention time at maximum temp.	24 hours
Number of cycle (20→200→20 degC)	40 times
Target value	SNR degradation < 10%

FIGURE 2. A test apparatus and test condition for temperature durability confirmation tests.

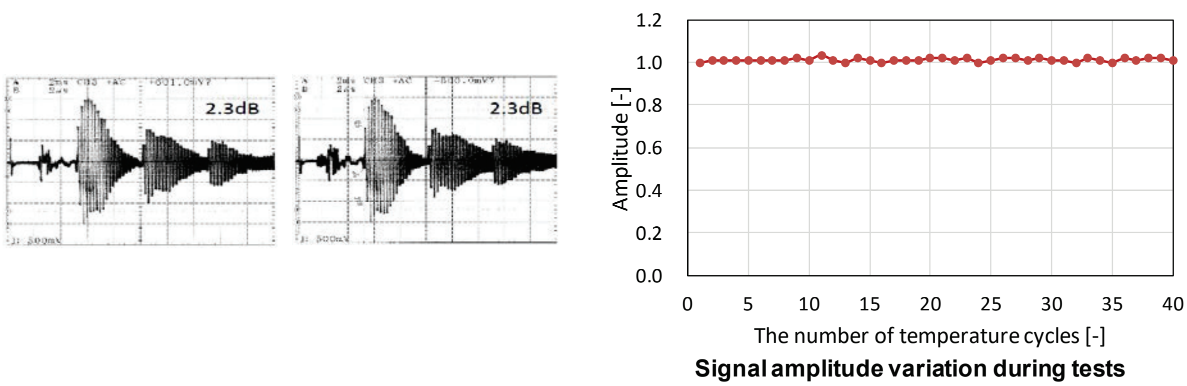
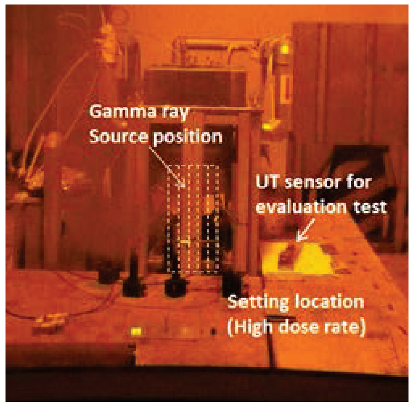


FIGURE 3. Comparison of wave forms and signal amplitude variation during the temperature cycle tests.

Irradiation Test

An investigation into irradiation durability of the sensor is also indispensable in order to introduce the non-contact ultrasonic sensor to the nuclear power plant inspection. For this, we performed irradiation test by using Gamma ray source. A test apparatus, a test condition and representative results are shown in Fig. 4. The sensor was bonded to the carbon steel specimen with the same adhesive as that of the temperature cycle tests. Total exposure and exposure rate of these tests are severer than those of the actual nuclear power plant condition. Due to very high exposure, oxidization occurred on the surface of the carbon steel specimen. However, significant difference was not observed around the transducer and the adhesive layer which is important to keep the measurement performance. As shown in Fig. 4, degradation of the signal amplitude was not confirmed during these tests. Thus, we have found that the sensor has sufficient durability against the irradiation in these test conditions. The further evaluation and experiments will be presented in the future study.



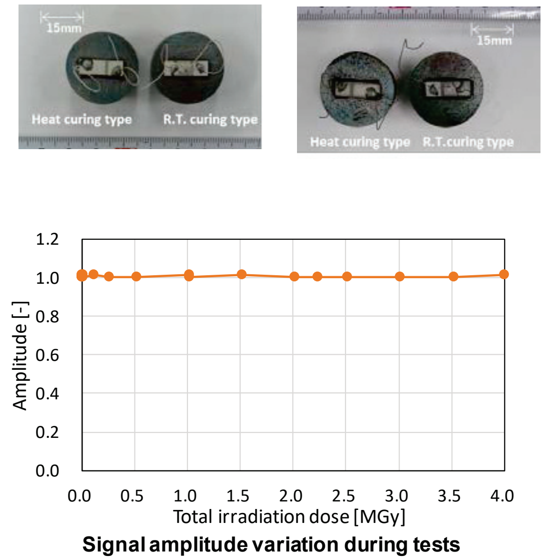
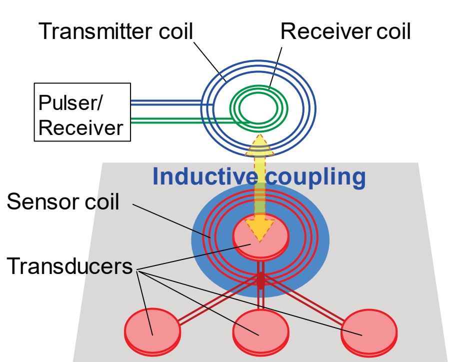


FIGURE 4. A test apparatus, test condition and representative results in the irradiation tests.

MULTI-TRANSDUCER SYTEM

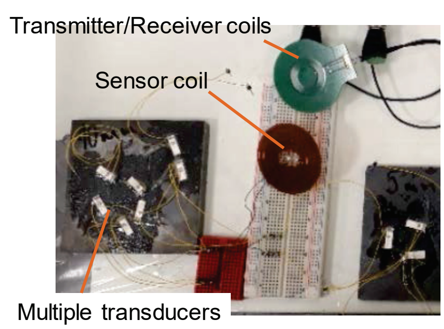
Concept and prototype sensor

Since one transducer is connected to one sensor coil in the non-contact ultrasonic sensor as shown in Fig. 1, the inspection rod needs to be held above each sensor coil to obtain the signal from each transducer. To reduce the inspection time further, we propose the multi-transducer system where multiple transducers are connected to one sensor coil as shown in Fig. 5. In this system, the signals from the multiple transducers are acquired through one sensor coil. Thus, the inspection time could be reduced by this system. Also, larger coil diameter can be deployable in this system because the coil diameter in the original system is limited by the pitch of the measurement points. To realize this concept, firstly we developed electrical circuit model by referring to that of the original non-contact ultrasonic sensor [9]. Based on the developed electrical circuit model, we optimized coil specification in order to meet the requirements shown in the right of Fig. 5. The number of the transducers in the manufactured prototype is changeable in order to investigate its effect on the measurement performance.



Concept of the multi-transducer system

Target frequency	5MHz
Size of coils	Around 50mm
The number of transducers	1, 2, 3, 4, 5



Prototype of the multi-transducer system

FIGURE 5. Concept of the multi-transducer system and the manufactured prototype.

Feasibility Confirmation

To confirm the feasibility of this concept, we performed several preliminary tests by using the manufactured prototype. Figure 6 represents a test apparatus, a test condition and representative results of the preliminary tests. The multiple transducers were deployed on the surface of the Aluminum pipe whose outer diameter and thickness are 170 mm and 10 mm respectively. Firstly, the wave form obtained by five transducers which were deployed on the same thickness measurement points was compared with that of the original non-contact ultrasonic sensor. The signal amplitude of the multi-transducer system was slightly decreased, but was still high enough to measure the thickness. Time of flight in both measurements was agreed well. Next, the number of the transducers was changed from one to five in order to investigate its effect on the measurement performance. As shown in Fig. 6, the signal to noise ratio was slightly decreasing with increment of the number of the transducers. However, even if five transducers were connected to one sensor coil, the signal to noise ratio was still high. Also the measurement accuracy was comparable to the conventional ultrasonic measurement. This means that the multi-transducer system would be feasible and further transducer could be connected to one sensor coil. It should be noted that the further development is required to introduce this system into the actual plant inspection (e.g. signal separation method and so on).

CONCLUSIONS

Aiming to reduce inspection time of the pipe-wall thinning measurement in nuclear power plants, we have been developing the non-contact ultrasonic sensor which enables the thickness measurement without removing the insulator covering the pipe. Measurement accuracy, maximum offset between coils and effect of the insulator on the measurement performance were investigated in the previous study. To introduce the non-contact ultrasonic sensor into the actual plant inspection, the sensor durability against temperature cycles and irradiation needs to be confirmed because the sensor is permanently attached on the pipe surface. In this study, we performed temperature cycle tests and irradiation tests which were simulating the actual plant conditions. These test results showed that the sensor would have sufficient durability against the temperature cycles and irradiation. Further test and evaluation will be performed in the future study. In addition to this, we proposed the multi-transducer system where multiple transducers are connected to one sensor coil for further reduction in the inspection time. To confirm feasibility of the multi-transducer system, we manufactured the prototype and performed preliminary tests by using the prototype. As a result, we have found that this system would be feasible even if five transducers are connected to one sensor coil. It should be noted that the further development will be required to introduce this system into the actual plant inspection.

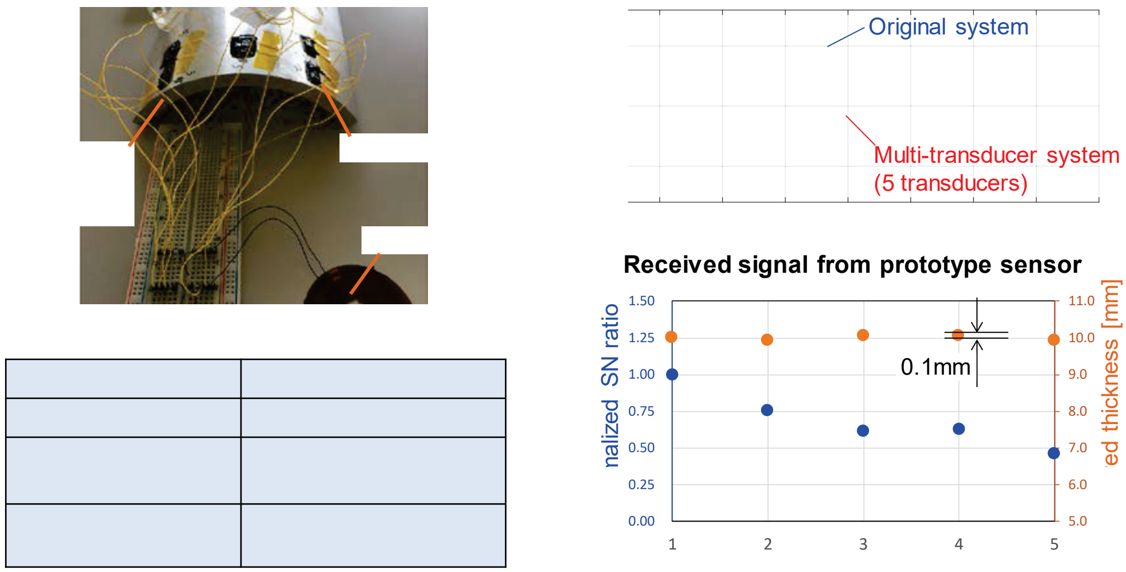


FIGURE 6. A test apparatus, a test condition and representative results of the preliminary tests by the multi-transducer system.

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