Development of the ISI Device for Fast Breeder Reactor MONJU Reactor Vessel*

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Abstract

In-service inspection (ISI) is carried out to confirm the integrity of the main components of the Fast Breeder Reactor (FBR) “MONJU”. The weld-joints are examined by using an inspection device which has a glass fiber scope for visual examination and a horizontally polarized shear (SH) wave electromagnetic acoustic transducer (EMAT) for volumetric testing. The ambient temperature during the inspection is 200°C and the irradiation field is 10 Sv/hr (Nominal value 3.5Sv/hr).

A new inspection device has been developed in order to improve the visual test performance, volumetric test performance and controllability of the inspection device reflecting the experience of the original test.

In this paper, detail of the new inspection device and the test results of sensors such as the CCD camera, EMAT and bead sensor are reported. The paper also reports on the CCD camera cooling system and other components.

Key words: Monju, Reactor Vessel, In-Service Inspection, CCD, Electromagnetic Acoustic Transducer

1. Introduction

In a nuclear power station, a reactor vessel is an important component. Therefore, in the light water reactor, an underwater robot (room temperature) [1,2] is inserted and the In-service inspection (ISI) by the ultrasonic using a piezo-electric device [3] is conducted for welding. ISI of the conical core support structure of the fast breeder reactor (FBR) “Phenix” in France is carried out using transducers through five penetrations of double barrier around the main vessel. [4]

However, FBR “MONJU” is inspected using an inspection device which runs automatically along weld lines of the reactor vessel. The items of ISI are visual test and volumetric test. However, due to the difficult environmental conditions around RV (high temperature and irradiation), until now, the weld-joints were examined by using an inspection device which has a glass fiber scope for visual examination and an electromagnetic acoustic transducer (EMAT) for volumetric testing on the inspection device. However, the visual examination was poor due to the 30,000 pixels of the fiber scope while the EMAT signal was small at higher temperatures.

In the present paper the development of a new inspection device consisting in an improved cooling CCD camera system and of a new EMAT equipment is reported. The new device has a higher inspection accuracy compared with the old one, providing better image resolution (410,000 pixels) and a higher signal/noise ratio during the volumetric testing even when it is operated in a high temperature environment (200 degree C).

2. Sketch out inspection device
Fig 1 is an in-service inspection system for the “Monju” reactor vessel. The inspection device is inserted in the 300mm gap between the RV and GV, and driven along weld lines by using a remote control cable 47m in length. The ambient temperature during the inspection is 200°C and the irradiation field is 10 Sv/hr (Nominal value 3.5Sv/hr). Verification and performance tests of the inspection device (Fig2)[5] were carried out during MONJU function tests (called SKS (Sougou Kinou Shiken)) in 1992. A new inspection device (Fig3) has been developed in order to improve the visual test performance, volumetric test performance and controllability of the inspection device reflecting the experience of the original test.

3. Visual testing

The purpose of the visual inspection is to detect sodium leakage traces on the surface of the RV. The machine used with SKS is called “SKS robot”. The new machine is called “new inspection device”. SKS inspection device carried out inspection with 30,000 pixels.
of fiberscope. The fiberscope has superior heat and radiation resistance but is easy to break. Therefore we developed a cooling system for a 410,000 pixels general CCD camera (Fig4).

Inspection environmental temperature and irradiation rate exceed a limit for the use of general CCD camera. Therefore the performance of the camera was evaluated in irradiation, heat and system tests. The CCD camera picture obtained in the heat and radiation resistance test is shown in Fig. 5. Test temperature is 70 degrees C which is the temperature attained with the cooling system. Irradiation rate is 3.5 Sv/hr. Because the end of life (30 years) for a nuclear reactor was assumed. The durability of a camera was checked for a maximum of 140 hr. because the inspection time required for a single ISI is about 110 hr(s) (100% inspection) which is a track record of SKS.[6]

![Fig4. Cooling system for CCD camera](image)

![Fig5. Image of CCD camera test (at 3.5 Sv/hr, 70°C (after cooling temperature))](image)

4. Development of other components

Experience of SKS can improve the controllability of the inspection machine. Furthermore, in order to decrease wear of a tire and to lessen exchange frequency, it is necessary to reduce the weight of the inspection machine. For this reason, targets of components for durability, controllability and light weight were taken as 200 degrees C and 200hr.

4.1. Development of Brushless DC Servomotors

The motor is carried in the inspection device for pushing an auxiliary wheel, driving and steering.

The SKS inspection device used an AC induction motor. However, a small lightweight brushless DC servo motor was developed.

A Samarium cobalt magnet was used for the rotor because it has less demagnetization at high temperature.
Furthermore, the SKS inspection device used a mechanical brake but the new servo motor could be used as a break thereby saving weight.

The developed motors are used for the drive of the GV side tire (SKS inspection device □70, 1.36kg⇒ new inspection device □52, 0.54kg), for the drive of the RV side tire, and for steering (SKS inspection device □60, 1.22kg⇒ new inspection device □39, 0.42kg). This produced a 50% decrease of weight. (Fig.6)

A rotation angle is detected by a resolver for high temperature. The resolver is directly linked with the motor.

![Fig6. Driving motor ( L : New, R : SKS ) Steering motor ( L : New, R : SKS )](image)

### 4.2. Development of stepping motors

A CCD camera is used for visual testing. For relation of a focal length and the view reservation, the camera picture is seen using a mirror. Therefore, a camera needs the motor turning around a mirror for inspection part.

The SKS inspection device used AC induction motor. However, even if there is no brake, it is possible to maintain a rotation position. Furthermore, stepping motor can open control that dose not need a position sensor. And the stepping motor which can carry out a light weight was developed. The sizes of a motor are □42x40mm and 280g.

It was checked by durability test at 200 degrees C for 200hr.

### 4.3. Development of resolvers

An angle sensor which to detect the rotation angle of a motor, and the position of inspection device are required. The SKS inspection device used the synchronization oscillator (φ19×45mm, 52g) for angle detection.

However, the synchronization oscillator machine had mechanical problems (a shaft bend, bushing damage, etc.) for long rotation.

The brushless resolver (φ25.4×22mm, 46g) with high angle detection performance, and with a short axis of rotation, and which can be used at high temperature was developed in order to solve this fault. Thereby, compared with the synchronization oscillator, durability became high.

Moreover, motor number of rotations was detected by the tachogenerator. However, the speed controllability of the new inspection device was improved by detecting using a resolver.

The resolvers were used for angle detection of a steering motor and angles detection (yaw, roll, pitch) of inspection device.

### 4.4. Development of tires
Two kinds of tires are used in the inspection device. The RV side use a metal tire which made from stainless steel. The GV side uses a rubber tires because friction power is required in order to support its weight.

It is important to maintain good tire condition because it determines the controllability of the inspection device. Therefore improved tire durability a required which will reduce exchange frequency. Silicone rubber and fluoride rubber were examined. Fluoride rubber was adopted as a result of the examination. Furthermore, wear and abrasion resistance was improved by enlarging the tire diameter (it is 107mm ⇒ 150mm about a diameter). Performance was examined at 10 Sv/hr (Nominal value 3.5Sv/hr) and 200hr(s), and the friction coefficient did not change. Furthermore, its performance against obstacles was tested because there are a level difference and piping for measurement of outer reactor.

4.5. Development of Harmonic drives™

Gears are used for the inspection device in order to increase the torque of the drive motor.

In the SKS inspection device, although the simple flat board gear was used, it became multi-stage structure, but this increased weight. On the other hand, a harmonic drive™ can obtain a high moderating ratio. However, an ordinary harmonic drive™ has a portion which uses resin, and cannot be used at high temperature. Therefore the resin part was changed to metal for high temperature operation. The optimal lubrication material was selected.

By using a harmonic drive™ safety is assumed since a self-lock is obtained with a servo motor.

4.6. Development of lamps

A strong light source because attenuation of light was large for 50m length of fiberscope.

Therefore, illumination was raised by passing a large current to a halogen lamp. But the decrease of the durability of the lamp by using a large current and the visibility by produced of halation were problems. For halation prevention, CCD was adopted and illumination was lowered.

A white lamp was adopted because the reproducibility of color is good.

Durability test was performed at 200 degrees C. Consequently, illumination decreased 17% but this did not influence inspection.

4.7. Development of Weld bead sensors

The reactor vessel has structure which used welded joints. Inspection is carried out on this welding. For this reason, the inspection device has a bead sensor (eddy current method) for detecting the position of welding. The SKS inspection device had a mechanical scan mechanism. The fixed-type bead sensor was developed for light weight.

The weld line width of the reactor vessel is about 10mm. The position detection range of the bead sensor was set as ±35mm.

It was developed for the purpose of the detection accuracy of ±2.5mm to welding with a bead width of 15mm. The form of a bead sensor adopted the differential coil composition type eddy current system (coaxial coil type). A differential coil composition type eddy current system detects a bead position using the potential drop between two coils. Although the center section of the sensor by which two coils touch has high linearity, linearity falls at the sensor end. For this reason, the coil was formed into many stages and the linearity of a detection domain was acquired. (Fig7) The bead sensor (size: about 150×30×25mm)
made as an experiment is shown in Fig 7.

As shown in Fig. 8, in ±35mm, the linearity relation independent of width between a bead position and a detection signal is from a bead center position. When there is no lift-off, detection of a bead is possible with an accuracy of ±1.0mm. It operated in the 200-degree C static environment for 300 hours. In an inspection environment, it has proved to be satisfactory.[7]
4.8. Changes to contact pressure system

The gap between RV and GV is not fixed (300mm±15mm) due to installation error, and thermal expansion. However, it is important to maintain stable controllability. The SKS inspection device adopted the straight spring structure. The new inspection device adopted the trapezoid spring structure for little change of power. (Fig10)

5. Volumetric testing

The volumetric testing of "Monju" RV ISI is near a weld line and near the primary cooling system piping. A horizontally polarized shear (SH) wave is insensitive to anisotropy, and no mode change occurs when the wave is reflected at an interface between materials or on material surface. Therefore, SH wave is a very suitable ultrasound mode to inspect the defects around weld areas of the reactor vessel. Additionally, SH wave can be easily excited and received by a SH wave EMAT. It is important to develop a stronger SH wave EMAT and confirm its characteristics not only at room temperature but also at elevated temperature for the application in MONJU reactor vessel ISI. Therefore, samarium-cobalt permanent magnet is more suitable for stable service at elevated temperature 200 degrees C. In the case of a SH wave EMAT, it can be satisfied by using Halbach magnet configuration instead of the general periodic permanent magnet (PPM) structure.[8] Hereafter, we abbreviate a SH wave EMAT with a Halbach magnet structure as Halbach EMAT, and a SH wave EMAT with a PPM magnet structure as PPM EMAT, respectively. A Halbach magnet structure is usually used in an undulator in an accelerator. The magnet structure and magnet flux density of PPM structure EMAT is shown by Fig11 (a). The magnet structure and magnet flux density of Halbach structure EMAT is shown by Fig11 (b).[9,10,11]
Fig 11. Magnet structure and Magnetic flux density of SH-wave EMAT

(a) Magnetic flux density distributions (PPM structure)

(b) Magnetic flux density distributions (Halbach structure)

Fig 12 illustrates the analyzed and measured magnetic flux density distributions in y direction at different lift-off distances from the working surface for Halbach and PPM structures, respectively. It can be seen that the magnetic flux density for the Halbach structure is stronger than that for the PPM structure. It is demonstrated that the Halbach EMAT has a more powerful magnetic property and larger ultrasonic sound pressure than the PPM EMAT. The ultrasonic sound pressure of SH wave for the Halbach EMAT can be as much as near 1.4 times that of the PPM EMAT. When receiver and transmission is added, it becomes the detection of two times. It is found that the measured magnetic flux density and the ultrasound directivity for SH wave EMAT are in very good agreement with the calculation results. Additionally, the Halbach EMAT reveals higher flaw detectability than the PPM one. The Halbach EMAT is an excellent tool in advanced non-destructive evaluation and testing.

Fig 12. Difference Magnetic flux density between PPM structure and Halbach structure

There are two kinds of signal processing. One is the method of deducting simply the signal (defect signal + resonance waveform) acquired near the defect, and the signal (only resonance waveform) acquired in the position distant from the defect, and it can extract only a defective signal comparatively easily.
The second is the method of deducting 2 signals obtained in the position which the wavelength of an ultrasonic wave shifted by 1/2 wave phase on the coaxial line which ties a defect and a flaw-detector machine. Detection is four times more than this.

By adoption of single EMAT of Halbach magnet structure, and adoption of the new signal processing method which shifted the phase, a transducer whose weight is 1/4 with 4 times the detection sensitivity compared with the existing transducer was produced (Fig.13).

![Fig13. Size comparison between PPM-EMAT (Left) and Halbach EMAT (Right)](image)

### 6. Conclusions

A new inspection device which can be used under high temperature and high irradiation environment was developed. A nitrogen cooled CCD camera is used for inspection. The new inspection device has better controllability by improvement of the software and reduction in the weight from 47 to 34 kg. The burden to tires decreased because weight is reduced. Consequently, the life became long and exchange frequency decreased.

The weight of EMAT decreased to 1/4 according to Halbach magnet structure. And by the new signal-processing method, the detection performance increased 4 times.

From now on, improvement will be continued using the 1/2 sector mock-up of Monju reactor vessel. Furthermore, the system which supports an inspector and inspection simulator is being developed.

### References


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