Development and Performance Test of the Combined Inspection System for In-Service Inspection of PGSFR Steam Generator Tubes

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1. Introduction

The steam generator (SG) tube in PGSFR has been designed to be made of a modified 9Cr-1Mo-V (G91) alloy due to its high creep and fatigue strengths. However, the G91 alloy is a ferromagnetic material which prevents the conventional eddy current testing technique [1] from being applied to its in-service inspection (ISI); defects located near the surface can only be detected owing to the skin effect. For ISI of such ferromagnetic tubes, therefore, a remote field eddy current testing (RFECT) technique which uses the magnetic energy diffusion penetrating through the tube wall has been employed. Although the RFECT technique is effective for detection of abnormalities in the thickness direction [2], however, it still has the difficulty for the detection of small and sharp defects such as cracks. In this work, an SG tube inspection system which combines the RFECT and magnetic flux leakage (MFL) [3, 4] techniques to have the better detectability not only for large thickness direction defects such as the wall loss but also for small and sharp defects has been newly developed for ISI of PGSFR SG tubes. And its performance was investigated through several damage detection tests conducted for G91 tube specimens having various types of defects.

2. Developed SG tube inspection system

The developed SG tube inspection system consists of a combined SG tube inspection sensor, signal analysis software and hardware.

2.1 Combined SG tube inspection sensor

Figure 1 shows the developed combined SG tube inspection sensor. It consists of a single exciting coil and two pickup coils for RFECT and a magnetic sensor array employing 23 Hall sensors arranged in the circumferential direction for the MFL testing. The length of the sensor is 90 mm and outer diameter is 12 mm slightly smaller than the inner diameter of the PGSFR SG tube. The RFECT sensor coils are installed at both sides of the sensor body while the magnetic sensor array is installed at the center of the sensor body. As a magnetic source for the MFL testing, a permanent magnet having 6 mm in diameter and 20 mm in length is employed and installed under the magnetic sensor array.

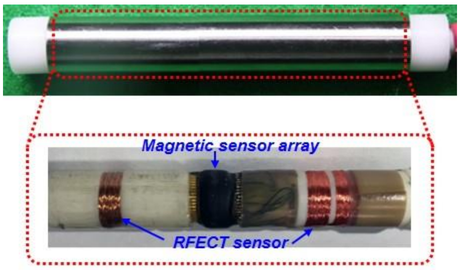

Fig. 1. Combined SG tube inspection sensor.

Using the developed combined sensor, RFECT and MFL inspections can be conducted simultaneously.

2.2 Signal analysis software and hardware

The signal analysis software developed for ISI of PGSFR SG tubes consists of acquisition, analysis and configuration modes as shown in Fig. 2(a). The developed software can perform RFECT and MFL inspections simultaneously by controlling inspection hardware. The measured RFECT and MFL signals can be analyzed by signal processing tools such as digital filters. The inspection hardware consists of the PXI system, a signal processing unit, two DC power supplies and an AC power supply as shown in Fig. 2(b). For efficient inspection and analysis, a controller, a digital lock-in amplifier, an A/D board and signal analysis software were integrated in the PXI system.

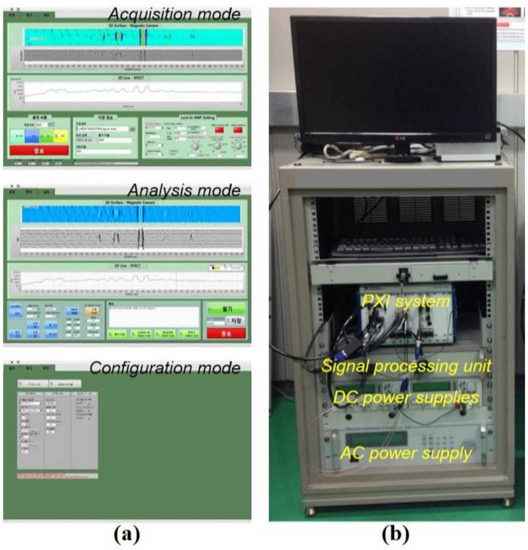

Fig. 2. (a) Signal analysis software and (b) SG tube inspection hardware.

3. Performance Tests

To investigate the performance of the developed combined inspection system, several damage detection tests were carried out for G91 test tubes having various types of defects with and without a tube support plate. And the test results were compared with those obtained by the commercial RFECT system.

3.1 Test facility

Figure 3 shows the test facility consisting of a tube supporter, a sensor moving device, a G91 tube support plate, a support plate moving device and a portable control box for the sensor moving device. Total 33 tubes can be installed in the tube supporter and the non-metallic support plate moving device was used to avoid its effect on the measured signal. The sensor moving device is employed for insertion and withdrawal of the sensor into and from the tube with a constant velocity and is automatically controlled by the signal analysis software through the portable control box.

3.2 Test Results

Figures 4(b) and (c) show the test results for one of G91 test tubes, which has five circumferential notches with different depths as shown in Fig. 4(a), conducted by the commercial RFECT sensor and the developed combined sensor, respectively. From the results, one can see that three defects having depths of 20%, 30% and 40% of the tube wall thickness are well detected by the developed combined sensor while no defect is detected by the commercial RFECT sensor. This is because the MFL technique has the higher sensitivity to small and sharp defects than the RFECT technique.

Test results conducted to investigate the effect of the tube support plate are shown in Fig. 5. For the test, a G91 tube having five short circumferential grooves with

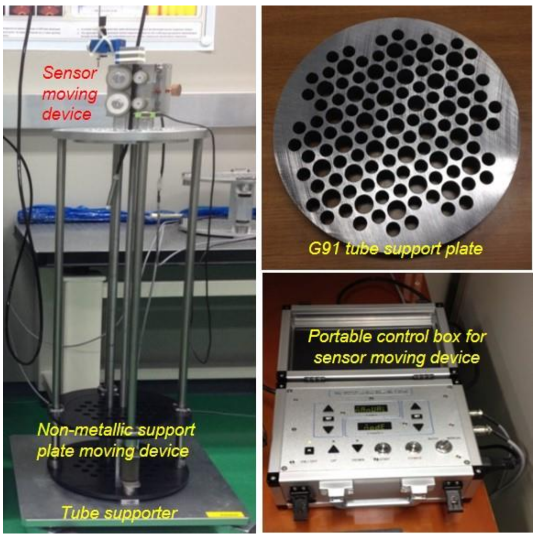

Fig. 3. Test facility.

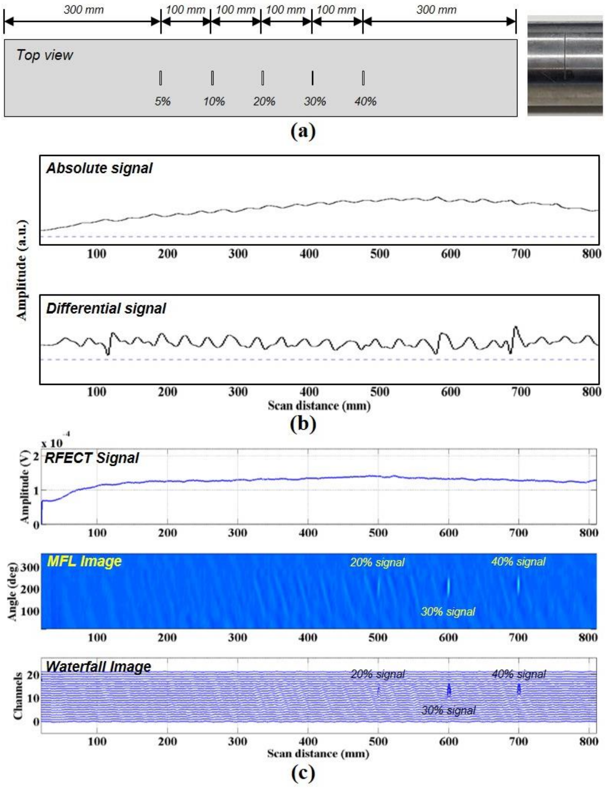

Fig. 4. (a) G91 test tube and test results conducted by (b) the commercial RFECT sensor and (c) by the developed combined sensor.

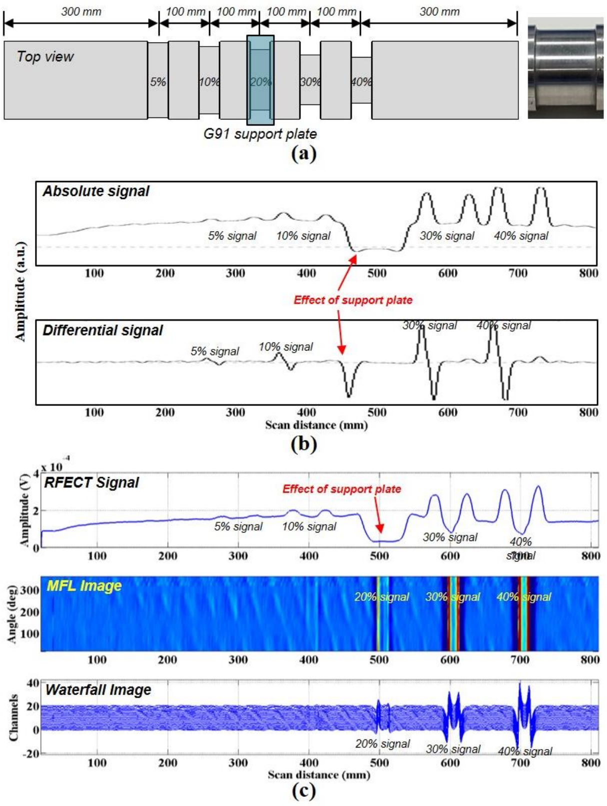

Fig. 5. (a) G91 test tube with a support plate and test results conducted by (b) the commercial RFECT sensor and (c) by the developed combined sensor.

different depths as shown in Fig. 5(a) was used as a test tube and the support plate was placed near the 20% defect. From the results, one can see that the defect near the support plate cannot be detected by the commercial RFECT sensor even though other defects including the 5% defect are well detected. This is because the metallic tube support plate significantly affects the distribution of eddy currents. On the other hand, it can be seen that the 20% defect is well detected by the MFL signal of the developed combined sensor. Although the support plate made of a ferromagnetic G91 alloy also affects to the MFL signal, the effect is not so significant because of the use of a permanent magnet having the relatively small magnetic intensity as a magnetic source for the MFL testing.

Another advantage of the developed combined sensor is well described in Fig. 6 where test results for a G91 tube having five defects with different distributions and depths but the similar cross-sectional area are illustrated. From the figure, one can see that defects having different distributions and depths can be well discriminated by the developed combined sensor whereas all defect signals having similar amplitudes are measured by the commercial RFECT sensor. Since two-dimensional inspection results can be obtained by the magnetic sensor array of the developed combined sensor, single and multiple defects can be well distinguished even though they have the similar cross-sectional area.

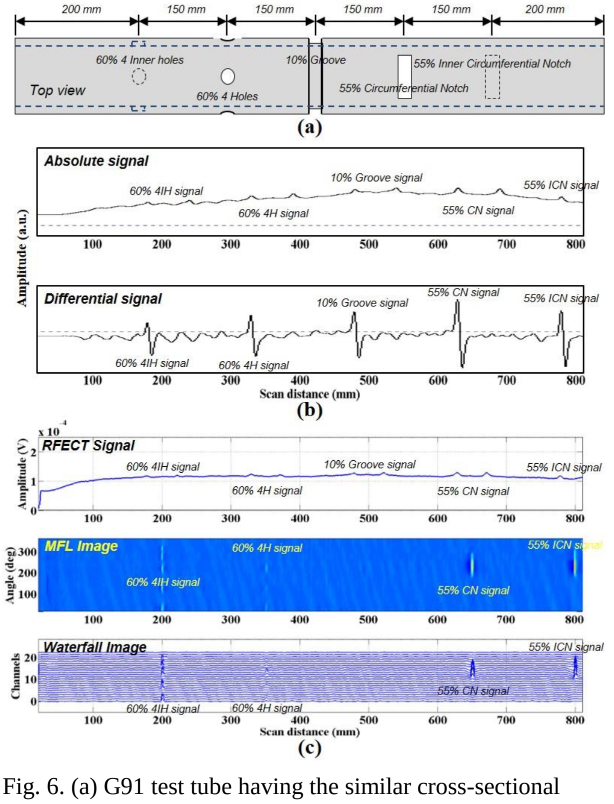

Fig. 6. (a) G91 test tube having the similar cross-sectional area and test results conducted by (b) the commercial RFECT sensor and (c) by the developed combined sensor.

4. Conclusions

The in-service inspection of SG tubes is one of most important parts for safe and efficient operation of PGSFR because the serious accident caused by the sodium-water reaction can occur if the SG tube has any defects. For efficient ISI of PGSFR SG tubes made of the ferromagnetic G91 alloy, therefore, the combined inspection system which can conduct RFECT and MFL inspections simultaneously has been developed. And its performance, particularly advantages compared with the commercial RFECT system, was clearly demonstrated through several damage detection tests conducted for G91 test tubes having various types of defects.

Acknowledgement

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