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Development of Non-Destructive Evaluation System for Rod Cluster Control Assembly Using Magnetic Imaging Technology

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1. Introduction

Fretting wear in a rod cluster control assembly (RCCA) is caused by vibration of the rods inside the guide cards during normal plant operation. It is a common concern in a pressurized water reactor design plant. Periodic inspection of the control rods is necessary to ensure structural integrity and maintain proper plant component functionality.

The expected life of the control rod assembly is about 15 years, but it can be shortened to about 10 years due to the occurrence of the above defects. Therefore, it's necessary to apply non-destructive testing methods to inspect the damages in early stage.

The current eddy current inspection technology uses differential enclosing probe and profilometry probe to measure average and local wear at the absorber filling area, but no technology is applied to measure micro-cracks in the circumferential direction of the end plug area.

This study aims to develop an encircling magnetic field camera that can detect circumferential cracking, fretting and sliding wear in control rods for the safe operation of a nuclear reactor.

2. Setup of RCCA Inspection System

2.1 RCCA

The RCCA in a nuclear reactor is a key device that controls and stops the reactivity of the reactor core. When the RCCA moves up/down in the reactor, it contacts with the guide cards cause of the vibration due to the coolant flow in the reactor vessel and causes fretting wear in the cladding tube. If the control rod is damaged and broken down, it can fall on the core, obstruct, and damage to the stable operation of the nuclear reactor.

Each control rod of RCCA has a cladding tube rod with a diameter of 9–11 mm and thickness of 0.47–0.49 mm made of stainless steel (STS304) cover a silver (Ag-80%) –Indium (In-15%) –Cadmium (Cd-5%) alloy radiation absorber. An end plug is welded with the cladding tube; hence, the absorber is isolated from the coolant.

The RCCA is shown in Figure 1. Table 1 shows a collection of 20 (16×16 type) and 24 (17×17 type) control rods. During the operation of the reactor, the RCCA is withdrawn from the inside of the nuclear fuel and supported by 8 guide cards located at the top of the reactor vessel.

Therefore, fretting wear may occur in the cladding tube by contact with the guide cards due to vibration caused by the coolant flow in the vessel [1]. In addition, in order to control or stop the reactivity of the core, sliding wear as the RCCA descends or rises, as well as end plug welding by Intergranular Stress Corrosion Cracking (IGSCC) may occur [2].

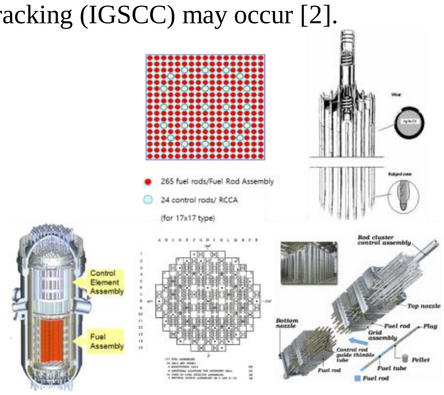

Fig. 1. Fuel rod assembly and rod cluster control assembly.

Table 1: RCCA parameters

Parameter	Westinghouse type		Korean Standard (OPR1000/APR1400)
	16 ×16	17 ×17	
No. of RCCA	33	52	73/93
No. of control rods /RCCA	20	24	4/12
Total length (mm)	4072.2	4088.1	6425
Absorption material	Ag-In-Cd	Ag-In-Cd	B_4C (Inconel 625)
Absorption length (mm)	3606.8	3606.8	3441
Cladding material	SS304	SS304	Inconel 625
Out diameter of cladding (mm)	9.32	9.68	20.73
Cladding thickness (mm)	0.44	0.47	0.889

The purpose of this study is to develop an encircling magnetic camera to detect cracks in the circumferential direction as well as freezing wear and sliding wear with a single sensor system. To achieve this purpose, an excitation bobbin coil and an encircling magnetic camera sensor probe were produced on each control rod of 17×17 type RCCA consisting of 24 control rods and 16 magnetic sensors arranged in an annular manner. A total of 384 magnetic sensors' signal processing circuits and remote DC and AC safety power sources are developed to establish a power supply and automated inspection system. A multiplexing circuit was developed to measure 24 control rods simultaneously, and a midsole processing unit equipped with NI-DAQ USB-6255 is produced for multi-channel AD conversion along with a secondary amplification unit to restore attenuated signals through a signal cable with length 17 m . In addition, measurement and analysis software and algorithms are developed using LabVIEW to image, database, and quantitative evaluation. In addition, the usefulness of the developed system will be verified using an RCCA artificial test specimen that introduces the defects of various shapes and sizes.

2.2 Inspection System for the RCCA

To measure individual control rods on a 17×17 type control rod assembly at the same time, the RCCA inspection system (Fig. 2) consists of (1) an inspection plate with 24 encircling magnetic cameras, (2) exciting coils, sensors, and signal processing circuits, and (3) a multiplexing unit including DC and AC stabilization power, and (4) an interface, computer and software.

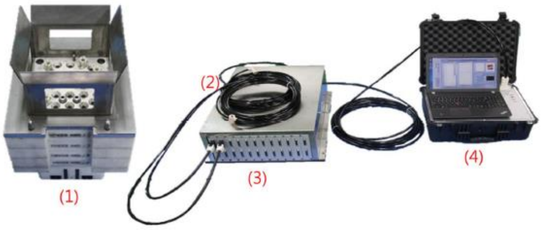

Fig. 2. RCCA inspection system: (1) inspection plate, (2) exciting coil, (3) multiplexing unit, (4) interface with computer and software.

(1) Inspection plate

The purpose of this study is to simultaneously inspect all 24 control rods consisting of the 17×17 type control rod assembly. Therefore, as shown on the left side of Fig. 3, an inspection plate developed by Korea Hydro & Nuclear Power and applied to the control rod assembly inspection was used. That is, 6 encircling magnetic cameras shown on the right side of Fig. 3 were placed on an inspection plate consisting of a total of 4 layers, so that 24 control rods could be inspected simultaneously when passing through the inspection plate. Figure 4 illustrates the guide of the control rod, and when the control rod passes through the sensor area, the lift-off between the sensor and the test piece is kept constant.

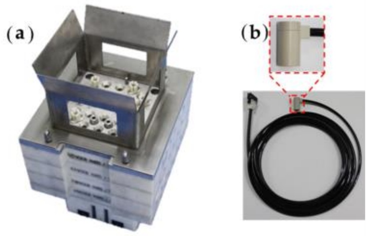

Fig. 3. Inspection plate (a) and sensor probe (b).

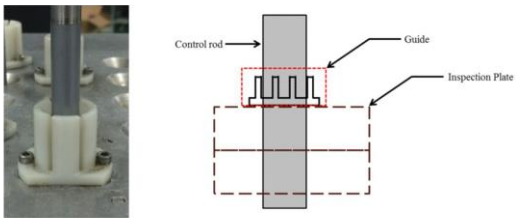

Fig. 4. Inspection plate guide.

(2) Exciting bobbin coil

As shown in Fig. 5, an exciting bobbin coil was manufactured to generate a time-varying electric field in the θ-direction, that is, an induced current, in the test specimen by inputting an alternating current. It shows the exciting coil to facilitate assembly and repair with the encircling array magnetic sensor. As shown in Fig. 6, it was designed and manufactured separately. A coated copper wire with a diameter of 0.1 mm was wound 220 times on a PEEK instrument with an average diameter of 15 mm and a width of 13 mm. In this structure, the distance from the surface of the specimen is 2.66 mm.

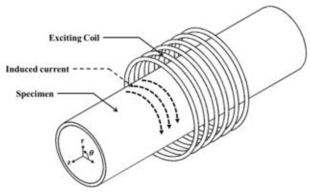

Fig. 5. Induced current on a tube specimen without cracks.

Fig. 6. Exciting bobbin coil.

(3) Multiplexing unit

- DC stabilization power source

The DC stabilization power source is manufactured for the purpose of supplying 5 to 24V power required to drive AC stabilization power sources and signal processing circuits including sensors, amplifiers, and filters. As shown in Fig. 7, the AC 220V is converted into DC power and 24V DC power is supplied to the sub-power units (b) to (f). It consists of a main power unit (a) and a sub power unit that decompresses and supplies 24V DC power supplied from the main power unit according to the purpose. (b) is a variable preliminary 12V DC power source, (c) and (d) supply ±24V positive power for signal processing circuits and AC stabilization power sources, and (e) and (f) supply 5V DC power source and used as sensor power and control power.

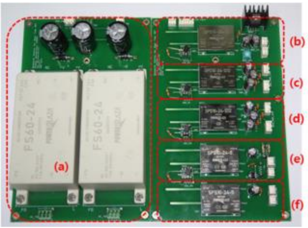

Fig. 7. DC power generation unit.

- AC stabilization power source

The AC stabilization power source is used to input AC power of 15 kHz, 120 mA, and 20 Vp-p to the coil mounted on the sensor head. When commercialized AC stabilization power is applied to achieve this purpose, the size and weight of the entire system increase (e.g., 10kg for Chroma 61602), increasing the load of workers, reducing work efficiency, and in some cases, increasing the amount of radiation waste. In addition, like DC stabilization power, remotely controlling the ON/OFF of the power without the operation of a separate switch or knob can lower the failure rate of the system due to work errors. In order to actively cope with this need, a remote control AC stabilization power source was developed as shown in Fig. 8.

The function generator (a) that generates a 15 kHz sine wave minimizes waveform distortion by adopting a dedicated IC, and the power amplifier (b) that amplifies the AC signal input from the function generator adopts a high-capacity capacitor and transformer to obtain a stable output even for a long time. On the other hand, aluminum heat sinks and small fan motors with good heat dissipation characteristics were applied to solve the problem of heat generation in the power amplifier when used for a long time.

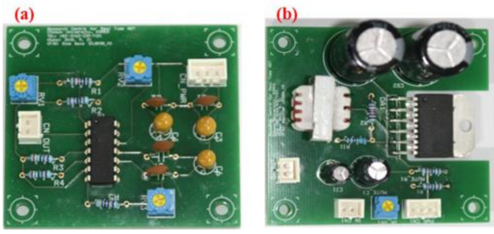

Fig. 8. AC power generation unit.

- Multiplexing circuit

Figure 9 shows the position of the encircling magnetic camera in the inspection flex. The encircling magnetic camera for inspecting each of the 24 control rods was divided into a total of 4 groups which consists of 6 cameras and each number refers to a sensor group that is operated at the same time. The simultaneous driving sensor group secured a sufficient separation distance to minimize interference caused by the excitation coil. In this configuration, signals are simultaneously input from a total of (16×4=) 64 hall sensors.

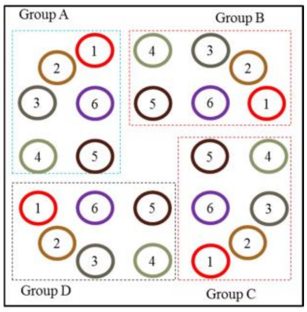

Fig. 9. Grouping of control rods for multiplexing process.

(4) Interface

In this study, NI-DAQ (USB-6255) was used for multi-channel AD conversion along with DC stabilization power AC stabilization power and multiplexing control. The USB-6255 (Table 2) can perform AD conversion of up to 80 channels and 16 bits. Figure 10 shows the central processing unit with the above-described secondary amplification unit and the interface.

Table 2: NI-DAQ USB-6255 specifications

Analog Input		Analog Output	
Analog Input Channels	80	Analog Output Channels	2
Analog Input Resolution	16bit	Analog Output Resolution	16bit
Maximum Voltage Range	± 10V	Maximum Voltage Range	± 10V
Minimum Voltage Range	± 100mV	Maximum Voltage Range	± 5V
		Current Drive All	5mA
Physical Specifications		Digital I/O	
Length	266.7mm	Bidirectoinal Channels	24
Width	170.9mm	Maximum Clock Rate	1MHz
Height	44.5mm	Logic Levels	TTL

Fig. 10. Main signal processing unit.

3. Conclusions

This study aims to develop an encircling magnetic camera to simultaneously detect cracks in the circumferential direction as well as fretting wear and sliding wear that occur in the reactor control rod with a single sensor system. To achieve this goal, 16 sensors were arranged annularly on each control rod of 17×17 type RCCA consisting of 24 control rods to quantitatively measure and evaluate the distortion of electromagnetic fields caused by the presence of defects.

For the future works the usefulness of the present system will be verified using the RCCA artificial test specimen representing the defects of various shapes and sizes.

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