Structural Health Monitoring of Nuclear Power Plants using Inverse Analysis in Measurements

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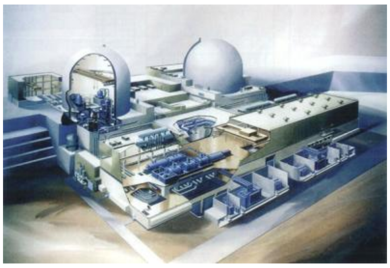
Abstract. Recently, interest has been grown for structural health monitoring related to ageing management of nuclear power plants (NPPs) in Japan. Especially, material failures in reactor containment have become a critical issue for safety of NPPs. Various kinds of nondestructive testing (NDT) techniques such as ultrasonic, eddy current testing, thermal testing, are applied to detecting and characterizing material damages like as stress corrosion cracking, piping wastage, etc. In this article, we show that modeling and simulation of NDT should be treated as a key component of the future structured monitoring technologies in NPPs. Our aim of this lecture is to show that the interaction between measurements and simulations of inspection process is an indispensable problem-solving methodology for implementing high performance monitoring of NPPs.

1. Introduction

Japanese utilities are currently operating fifty five nuclear power plants and cover about thirty percent of the total electricity generated in Japan. Nuclear power generation has been considered as a clean energy source with no carbon dioxide emissions. However increasing ageing plants need keeping a high level of safety and improving the safety of older nuclear power plants. Periodic safety review (PSR) is to assess the cumulative effects of plant ageing and plant modifications, operating experience, technical developments [1]. The reviews include an assessment of plant design and operation against current safety standards and practices, and they have the objective of ensuring a high level of safety throughout the plant’s operating lifetime.

Most Japanese nuclear power plants consist of the pressurized water reactor (PWR) and the boiling water reactor (BWR) as shown in Fig. 1. PWRs are the most common type of power producing nuclear reactor and there are two separate coolant loops. Heating the water in the primary coolant loop by thermal conduction through the fuel cladding and it is pumped into the steam generator, where heat is transferred to the lower pressure secondary coolant. On the contrary, BWR has only one coolant loop. Heat is produced by nuclear fission in the reactor core and the producing steam is directly used to drive a turbine. In PWR, the steam generator tubes constitute one of the primary barriers between the radioactive and non-radioactive sides of the plant. Therefore, in-service inspections of the steam generator tubes are essential in keeping safety of operations. In BWR, the core shroud is a large stainless steel cylinder of circumferentially welded plates surrounding the reactor fuel core. The shroud provides for the core geometry of the fuel bundles. Extensive cracking of circumferential welds on the core shroud has been discovered in a increasing number of Japanese BWRs plants since 2002. In such a situation, it is becoming clear that the aging of reactor components poses serious safety risks at NPPs. In Japan, a committee on ageing



(a) PWR

(b) BWR

Fig. 1 Bird's eye view of nuclear power plants

management was established in the Nuclear and Industrial Safety Agency (NISA) which is a reorganization of central government ministries. The committee has confirmed the NISA report on improved ageing management in 2005 [2]. Technical evaluation review manuals for ageing management published by Japan Nuclear Energy Safety Organization (JNES) include the following eight degradation phenomena:

(1) Neuron irradiation embrittlement of reactor vessels
(2) Stress corrosion cracking, such as intergranular stress corrosion cracking (IGSCC), primary water stress corrosion cracking (PWSCC), irradiation-assisted stress corrosion cracking (IASCC), etc
(3) Fatigue
(4) Thinning of pipeing, such as flow accelerated corrosion (FAC), Liquid droplet impingement erosion (LDI), flashing erosion, cavitation erosion, etc
(5) Insulation degradation of electrical cables of instruments and control facilities
(6) Strength and shielding capability degradation of concreate
(7) Seismic safety evaluation
(8) Viewpoint and understanding of approaches to prevention for organization culture degradation

Stress corrosion cracks, such as IGSCC, PWSCC, and IASCC, are the critical phenomena of ageing management and NISA has performed their technical evaluations at every ten years after thirty years operation. To accomplish PSR for those components mentioned above, it is more important to verify the sizing accuracy of a material damage with the technology of non-destructive inspection applied to real plants and the feasible guideline will be developed to judge the adequacy of inspection.

In this paper, we discuss structural health monitoring of NPPs. Structural health monitoring (SHM) is an upcoming technology in keeping safety of large scale complex systems, such as nuclear power plants, airplanes, etc. SHM involves the broad concept of assessing ongoing and in-service performance of structures using variety of measurements. Those elements include sensors in structures, data acquisition, data management, data interpretation, diagnosis, etc. For convenience of discussions, the problem is focused into the characterization of stress corrosion cracking (SCC) of stainless steel used in recirculating pipe and in shroud in BWR plants. This paper is organized as follows. First, direct and inverse problems are mathematically formulated based on advanced electromagnetic nondestructive evaluation. Secondly, data interpretation and diagnosis are discussed within the framework of parameter identification method. Finally, current achievements are summarized with laboratory experiments.

2. Role of Simulation and Modeling

To ensure a high level of safety throughout the plant's operating lifetime, in-service inspection (ISI) had been performed at every thirteen months of operation until 2008. Recently, Japanese utilities must implement a new safety regulation related to ageing management. In that process, a inspection cycle might be varied corresponding to operational conditions of each plant. This implies that the precise management for material failures are required. For instance, as shown in Fig. 2, if a crack has been detected in the current ISI, it is necessary to predict the crack progress in the next ISI and to judge whether the predicted progress exceeds the safety standards. The feasibility and reliability of quantitative non-destructive evaluation must be studied. Simulation of inspection procedures and modeling of material failures of reactor plants are crucial parts at the course of this investigation. In this sequel, we deal with the mathematical framework of our SHM system. For convenience of discussions, the problem is focused into the characterization of stress corrosion cracking (SCC) of stainless steel used in recirculating pipe and in shroud in BWR plants.

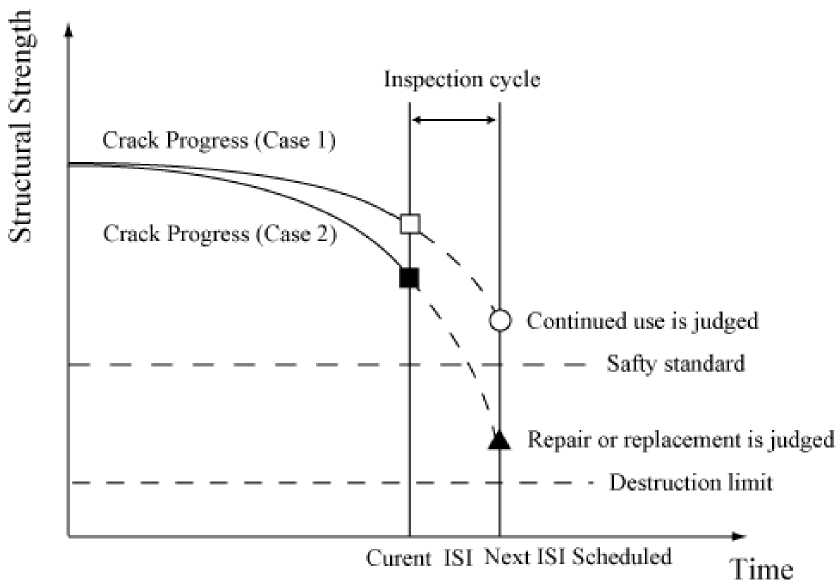


Fig. 2 Illustration of structured integrity evaluation

3. General Framework of Model Based Approach

Electromagnetic nondestructive testing is to find material flaws by evaluating structure sensitive electromagnetic properties from measurement data using appropriate sensors. Mathematical descriptions of NDT can be formulated as a direct and an inverse problem in electromagnetic fields [3-5]. A direct problem is to design a real NDT system mathematically using the input and output relation with the appropriate admissible class of material flaws, while an inverse problem is to construct a method for recovering and/or visualizing material flaw information under the mathematical formulation of the direct problem. Figure 3 demonstrates the overall configuration of our proposed system. In order to implement the system, we need the following four steps:

Step 1: Mathematical Modeling of NDT and Defect Profiles
Step 2: Numerical Scheme for Direct Problem
Step 3: Inverse Analysis for Model-based NDT
Step 4: Performance Test

4. Mathematical Model of Inspection

Eddy current analysis can be implemented by measuring voltage of detecting coil corresponding to the applied current of the exciting coil. Multiple transmitter-receiver coils have the capabilities of detecting crack orientations and distinguishing the adjacent cracks by choosing the transmitter-receiver pairs [6]. This new type of probes makes it possible to capture natural cracks, such as stress corrosion cracks (SCC), fatigue cracks

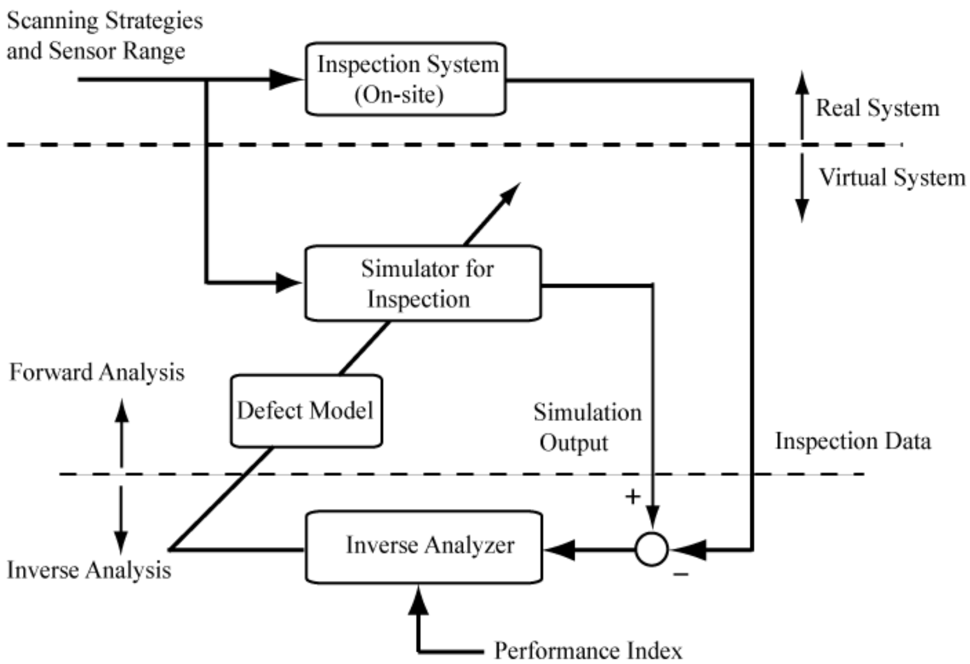


Fig. 3 Overall configuration of model based diagnosis system

(FC), etc. Let $B = \nabla \times A$ be magnetic flux density that has a complex phasor representation in three dimensions. The magnetic vector potential $A = (A_1, A_2, A_3)$ at the neighborhood of the exciting coil is governed by an Euler equation

$$-\frac{1}{\mu_0}\nabla^2 A = \chi_c \circ J_s \tag{1}$$

where μ_0, χ_c, and J_s denote the magnetic permeability, the characteristic function with respect to the exciting coil, and the amplitude of the applied current, respectively. The eddy current generated in a conducting material can be derived from the diffusion equations:

$$-\frac{1}{\mu_0}\nabla^2 A + j\omega\sigma(A + \nabla\Phi) = 0 \tag{2}$$

$$\nabla \cdot j\omega\sigma(A + \nabla\Phi) = 0 \tag{3}$$

where σ and ω denote the electrical conductivity and the angular frequency of the applied current. By virtue of the Biot-Savart's law, the detecting voltage can be obtained by

$$V_d \propto -j\omega N_t \oint A_c \bullet dl \quad . \tag{4}$$

where N_t and A_c denote the number of turns of the detecting coil and the magnetic vector potential at the detecting coil given by

$$A_c(x) = j\omega \iiint_V \frac{\sigma(A + \nabla\Phi)(x')}{|x - x'|}\, dx' \quad . \tag{5}$$

From the numerical points of views, the finite element method is a simple scheme and is easy to implement to solve the above problem. However it requires re-meshing at each measurement point. This re-meshing procedures result in considerable amount of computational efforts for the problem considered here. In our approach, the hybrid scheme of the finite element and the boundary element method [7] is adopted to the forward problem. The hybrid scheme of the finite element and the boundary element method is an effective method for the computational cost. Thus our numerical scheme is written by

$$\left([P] + j\omega[Q](\sigma_h) + [K]\right)\begin{Bmatrix} A_h \\ \Phi_h \end{Bmatrix} = \begin{Bmatrix} F(J_s) \\ 0 \end{Bmatrix} \tag{6}$$

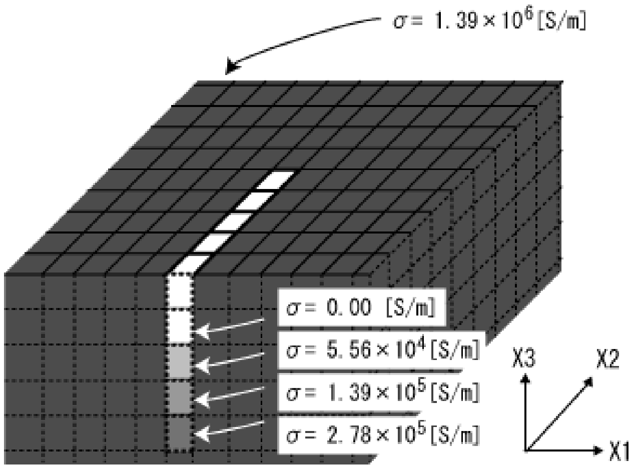


Fig. 4. Modeling of stress corrosion crack in finite element analysis

where P and Q denote the finite element matrices corresponding to conducting region and where K denotes the boundary element matrix associated with the air region, respectively. In the numerical model, the existence of cracks is characterized by the intensity of electrical conductivities at each finite element as illustrated in Fig. 4.

5. Inverse Analysis for Model-based NDT

One possible way to solve such inverse problem is shown in Fig. 5 [8]. In the procedure, the database stores knowledge about ECT signals of cracks with different sizes and various scanning parameters, such as driving frequency, scanning patterns and scanning positions. Pre-processing examines measured images to determine crack length and position and to prescribe possible crack depth. After this step, a set of crack with initial size and position is created to be the input for the next step. A set of crack with possible size and position is created and finding peak value of measurement voltage and comparing with measurement results allow us to determine possible depth of crack created from process. Thus the proposed algorithm can set up possible the size, position, and depth of cracks. The output of Pre-process is a set of cracks with possible size and position, to be the input for the next process. Figure 6 depicts the real image for the natural crack, the recovered image, and the recovered crack shape.

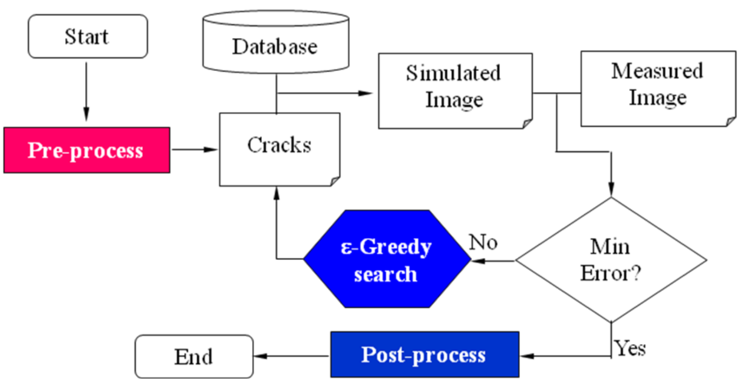
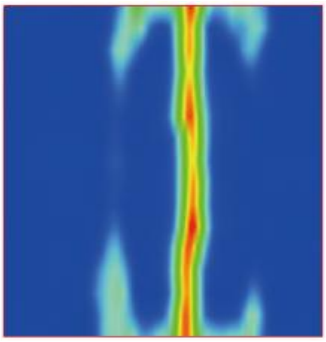
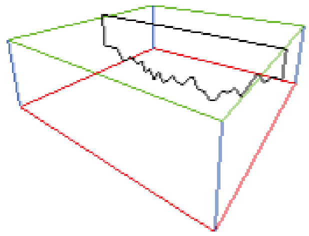


Fig. 5 Flaw chart of crack shape recovery



(a) Measurement image by ECT



(b) Reconstructed crack shape

Fig. 6. Experimental results with laboratory data

6. Conclusions

In this article, it was shown that modeling and simulation of NDT is indispensable problem-solving methodology for implementing high performance monitoring of NPPs. Electromagnetic inverse methodologies for sizing stress corrosion crack were considered for boiled water reactor (BWR) plants. It is very crucial to characterize target cracking of SUS304 and SUS316L materials used in BWR plants since those involve various kind of complexities, such as orientation, multiple deep-lying branching, partially conducting, etc. The model based health monitoring system was outlined for sizing natural crack in three dimensions. The feasibility and validity of our inverse algorithm using laboratory data were demonstrated.

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