

1-2 Large Scale ECT to Simulate ISI of Ferromagnetic SG Tubes of FBR

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要旨

The paper presents developments and numerical simulations of eddy current testing (ECT) algorithms used during In-Service Inspection (ISI) of ferromagnetic steam generator (SG) tubes of Fast Breeder Reactors (FBR) as in Monju FBR. A 3D FEM code was developed and enhanced to use parallel computing in our laboratory in order to take advantage of JAEA supercomputer and use up to 1024 CPUs. Both OpenMP and MPI libraries were added in pre-solver FEM assembling part and iterative solver. Finite element method (FEM) simulations are used to simulate different areas of ISI of FBR SG tubes as support plate and U-bend part with various sodium structures.

1. 研究目的

The purpose of the research was to develop a numerical 3D tool in order to simulate the ISI of FBR SG tubes using eddy currents and to validate the results also for the case when sodium structures are located outside of SG tube.

2. 評価方法

In Fast Breeder Reactors (FBRs), one of the techniques used in the In-Service Inspection (ISI) of magnetic steam generator (SG) tubes is the eddy current technique (ECT). The SG tubes, made of 2.25Cr-1Mo alloy are fixed in a helical structure shape using multiple support plates (SP) which are also ferromagnetic. The complicated shape of the SP and the multiple connections of several tubes to the SP can be quantitatively analyzed only in a full 3-dimensional (3D) analysis, in order to evaluate the influences in the ECT signal due to the close proximity of the SG tubes.

In a SG mock-up, the SG tubes are supported using only a reduced geometry version of the SP. However, in the reactor, there are multiples SG tubes connected to a big SP and the ECT signal from the SP can varies according to the position of the SG tube in SP.

The code is based on the FEM in the Galerkin approach, starting from the Maxwell electromagnetic equations and uses the magnetic vector potential defined as $\vec{B} = \nabla \times \vec{A}$.

The 3D FEM model is based on (A-V) field formulation with the gauge of the electric scalar potential $V=0$ (in order to reduce the computational burden due to the 3D model). The magnetic vector potential A is divided in two terms as follows: \vec{A}_S – the vector potential of the source field in the free air (calculated with the Biot-Savart law) and \vec{A}_R – the reduced magnetic vector potential, due to the presence of the ferromagnetic region. By adopting the reduced magnetic vector potential, the source and detection ECT coils are not meshed in the FEM model. The electromagnetic field in the 3D-RFECT code is modeled by the Eq. (1).

$$\begin{aligned} \nabla \times (\nu \nabla \times \vec{A}_R) - \nabla \cdot (\nu \nabla \cdot \vec{A}_R) &= 0, & \text{in } \Omega_1 \\ \nabla \times (\nu \nabla \times \vec{A}_R) - \nabla \cdot (\nu \nabla \cdot \vec{A}_R) + \sigma \frac{\partial \vec{A}_R}{\partial t} &= -\nabla \times (\nu \nabla \times \vec{A}_S) - \sigma \frac{\partial \vec{A}_S}{\partial t}, & \text{in } \Omega_2 \end{aligned} \quad (1)$$

The code was parallelized using MPI, OpenMP and block-caching algorithms at both matrix assembling stage and solver solution. The iterative solver convergence was accelerated using various pre-conditioner techniques: ILU0, nodes reordering and by modifying the electromagnetic equations with an additional null term that change the regularization of FEM matrix.

Numerical methods based on three dimensional FEM using the developed 3D-RFECT code in our group to model electromagnetic effect of sodium, and estimates the maximum noise arising from sodium deposition. Modeling focuses on the multiple interactions among sodium, tube, and tube support plate, because those signals could mask outer SG tube defects. Two models of SP, presented in Fig. 1 were taken into consideration: a small model of SP with one SG tube (Fig. 1a) and a large SP model (Fig. 2a) with many SG tubes (nine in the present paper). While the small SP model is used in a mock-up test, the large SP model with multiple SG tubes resembles more the real situation in a FBR reactor.

Sodium forms, shown in Fig. 2b, are filling the void between SP and austenitic-stainless steel ring connecting SP and SG tube. Standard groove defects are located mainly in the vicinity of SP, resulting from the fretting-wear mechanism between SP and SG tube. Their position (A) and (B) is indicated in the schematics in Fig. 2a. Both defects are under the main two legs of SP.

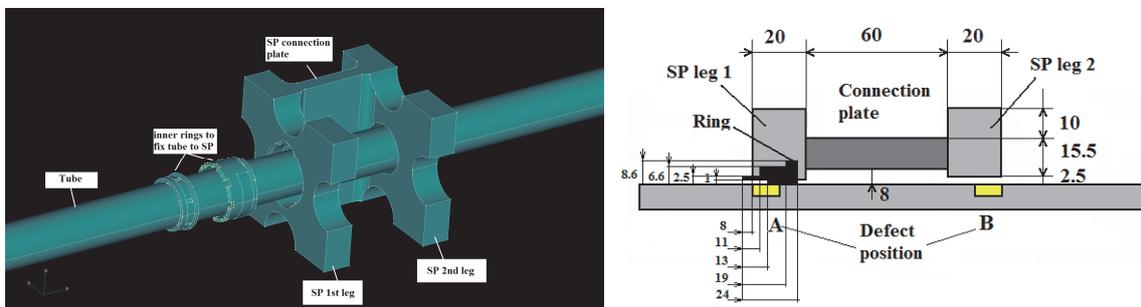


Fig. 1. Geometry and schematics of small SP with a single SG tube

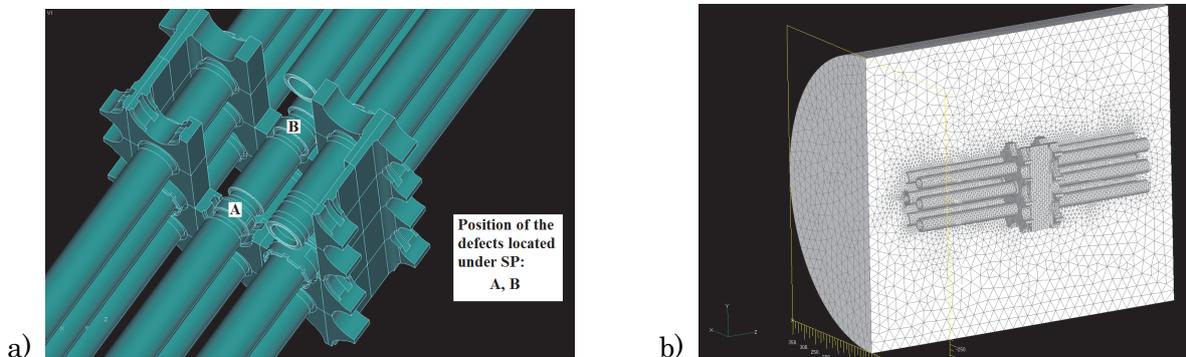


Fig. 2. a) Geometry of large SP with nine SG tubes and defects located under SP; b) FEM model for a large SP with nine SG tubes

The model uses up to 3,000,000 2nd order tetrahedral elements requiring use of parallel computing with up to 1024 CPUs using BX900 JAEA supercomputer. Simulation of 150 scanning points requires almost 12 hours of computation (1024 CPUs).

FEM numerical simulations of the distribution of the magnetic vector potential, using the 3D-RFECT code, is illustrated for the case of the large SP with multiple SG tubes in Fig. 3. The RF-ECT sensor is located in a central SG tube completely surrounded by other 8 tubes. The excitation sensor locations in the RF-ECT system correspond to the red zone on the tube while the sensor location is between them. Simulations of the amplitude of SP signal and field visualizations show that there is a shielding electromagnetic effect due to surrounding SG tubes, that is decreasing the signal from SP by up to 20%.

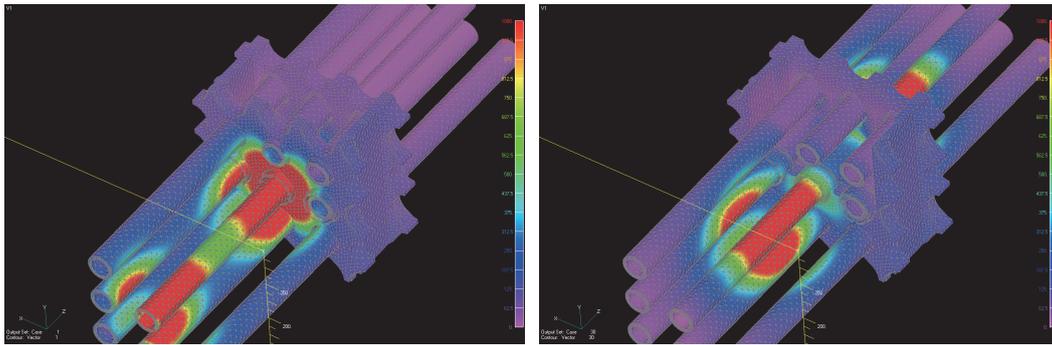
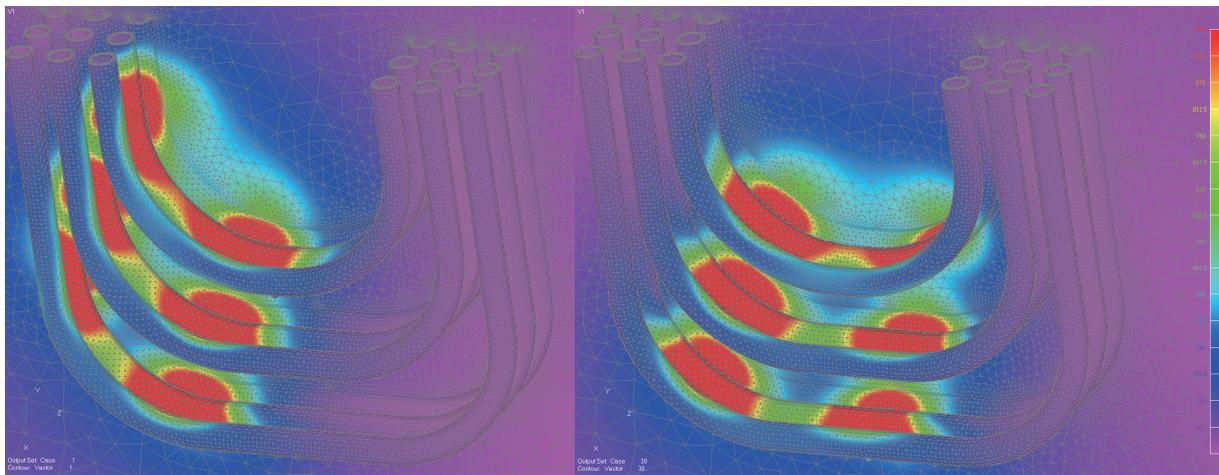
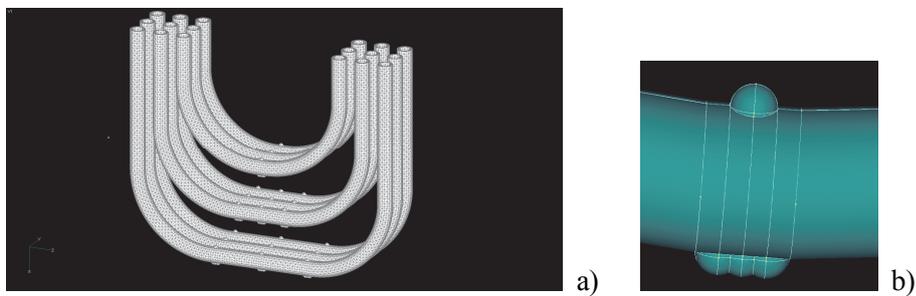


Fig. 3. Simulation of distribution of the magnetic vector potential when RF-ECT sensor inspect the SG tube located in the middle of SP and surrounded by other eight SG tubes



c)

Fig. 4. a) FEM model of multiple U-bend tubes with various curvature; c) Model of sodium drops located outside of SG tube; c) Simulation of distribution of the magnetic vector potential in U-bend SG tubes with sodium drops located on

Development and validation of the 3D RF-ECT code was realized with both experimental and theoretical solutions for simpler geometries. The main innovative parts in this work was to find a suitable electromagnetic formulation which could be scale to work with many CPUs and to parallelize the code and the iterative solver those convergence usually worsen as the simulation problem increase in size. New parallel algorithms were developed in order to take full advantage of JAEA supercomputer. Another innovative works was related to validation of 3D electromagnetic models of ISI using ECT for both cases: SG tubes without sodium and with sodium structures.

Based on 3D simulations and validations ECT probes could be enhanced for better detection of defects in SG tubes of FBR.

3. 評価結果

Development of the 3D code to simulate ISI of SG tube using eddy currents enable analysis of large structures of SG tubes with geometry similar with SG tubes of Monju FBR or future FBR. Innovative approaches were added in both code development in order to be able to scale the code to a large number of CPUs (up to 1024) and using two parallelization schemes (MPI and OpenMP). It was shown that the 3D code model provides a higher resolution with complex SP structure conditions, where the amplitude of defect (OD20%tw) is limited to only a 20-30% reduction but without changing significantly the defect signal/noise ratio from the case of one SG tube to the case of many SG tubes connecting to SP. Also, it could be simulated and validate the noise from sodium drops near support plates or U-bend tubes.

本稿に関する投稿論文

- [0-1] Ovidiu Mihalache, Toshihiko Yamaguchi, Masashi UEDA, Shinya Miyahara, "3D Remote Field-Eddy Current Simulations of the Support Plates of the Magnetic Steam Generator Tubes in FBR", 7th NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, Yokohama, May 12-14, 2009.
- [0-2] Ovidiu Mihalache, Toshihiko Yamaguchi, Masashi Ueda, " Advancement and Performance in Large Scale Eddy Current Simulations for ISI of FBR Steam Generator Tubes", Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2010 (SNA + MC2010), Tokyo, 2010.