1-3 Multi-Frequencies ECT Algorithms to remove sodium noise in ISI of Ferromagnetic SG Tubes of FBR

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要旨

The paper presents developments and application of multi-frequency eddy current to be used during In-Service Inspection (ISI) of ferromagnetic steam generator (SG) tubes of Fast Breeder d Reactors (FBR). Signal enhancement by means of multi-frequency ECT techniques are validated through 3D simulations of both signals and noise due to sodium forms around SG tube or SP. The purpose of such algorithms is to remove from ECT signal the electromagnetic noise resulting from sodium accumulated outside of SG tubes after SG vessel draining. Finite element method (FEM) simulations are used to analyse different sodium build-up scenarios observed experimentally, and to determine optimal multi-frequency ECT algorithms to suppress the most efficiently sodium noise. Also a new "window multi-frequency" algorithm is applied and validated using 3-dimensional FEM simulations of SP and sodium forms.

１. 研究目的

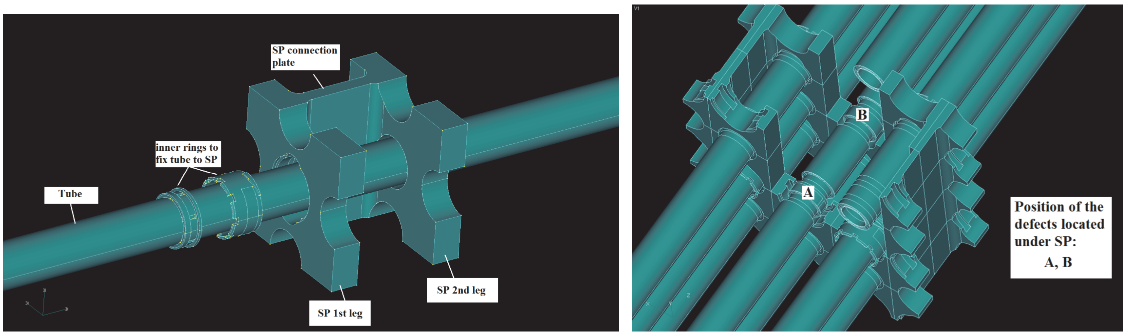
The purpose of research was to check and validate the feasibility of applying standard and a news developed multi-frequency algorithms to be applied to the removal of sodium noise from the ECT signal using numerical 3D FEM simulations when taking into account both large SG tubes SP plates and multiple tubes.

２. 評価方法

In Fast Breeder Reactors (FBR) using liquid sodium as a coolant, In-Service Inspection (ISI) of Steam Generator (SG) tubes based on Eddy Currents Testing (ECT) has to consider the electromagnetic interferences from the conductive sodium. Because sodium is highly conductive, ECT signal during ISI is polluted by sodium signal and a through analysis is required to understand signal variation especially near large SP structures. In the numerical simulations of ISI of FBR tubes using ECT, the variability of sodium forms and positions along SG tubes and structures around SG tube has to be taken into account in the most conservative case, and even if those shapes were actually not observed in the limited number of experimental measurements. ISI feasibility of FBR SG tubes using ECT should take into account accurate numerical modeling of all electromagnetic noises due to coupling of sodium with tube discontinuities, SP, or other structures around SG tubes.

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. While experimental measurements showed only partially filling of defects or void gap with sodium, in the 3D computational model it were introduced models of sodium forms that would represent the worst cases which could be ever observed experimentally. Two models of SP, presented in Fig. 1 were taken into consideration: a small model of SP with one SG tube and a large SP model with many SG tubes. 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, are filling the void between SP and austenitic-stainless steel ring connecting SP and SG tube. Standard groove defects (position A and B) are located mainly in the vicinity of SP, resulting from the fretting-wear mechanism between SP and SG tube.



b)

Fig. 1.) Geometry of SG tube with small or large SP and defects located under SP

The main innovation of the present research is to check and prove the feasibility of applying multi-frequency ECT in order to remove the electromagnetic noise due to the unknown sodium distribution located outside of SG tube. Based on experimental measurements we know sodium distributions and sodium drops sizes. However, using 3D numerical simulations, is it possible to validate the multi-frequency algorithms with the worst case scenario, even for the moment this scenario could not be recorded experimentally during the limited set we could measure in our mock-up tests.

In the multi-frequency ECT algorithm two detection signals of the RF-ECT sensor at different frequencies are combined in order to minimize the noise in the signal. If we consider that signal at frequency ν1 is C1 and signal at frequency ν2 is C2 , then the multi-frequency algorithm first map the signal C2 to signal C3 at frequency ν1. The multi-frequency signal S is then computed after reducing the initial signal C1 by the mapped signal C3. Each signal (C1, C2 and C3) have two components related to the resistive and inductive components respectively.

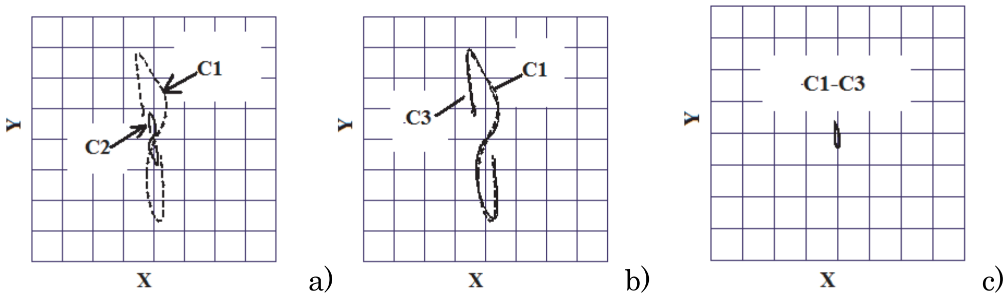


Fig. 2. Schematic of the multi-frequency ECT technique: a) initial signals at two different frequencies; b) mapping of signal from one frequency to the other; c) multi-frequency signal

When using a single ECT frequency is difficult to make a difference between a sodium signal and a defect signal. Also, because we do not know the size of sodium structure and how much can fill gaps or defects, the ECT signal can vary large making difficult to have a clear interpretation/analysis of signals.

In the ISI of FBR SG tubes, the signal of noise is considered to be the combined signal from tube SP and sodium. Because of the non-linear effect of the sodium to the RF-ECT signal, the mapping of the multi-frequency algorithm is based on a linear algorithm, which is more robust against unknown non-linear behavior of input signals. However, because there are variations in the SP signal due to sodium filling the air-gap between SP and SG tube, for each sodium form, a multi-frequency algorithm can be determined to reduce to a minimum the SP signal. Among all multi-frequency algorithms, it is chosen the one that minimize the difference (C1-C3) for all sodium forms.

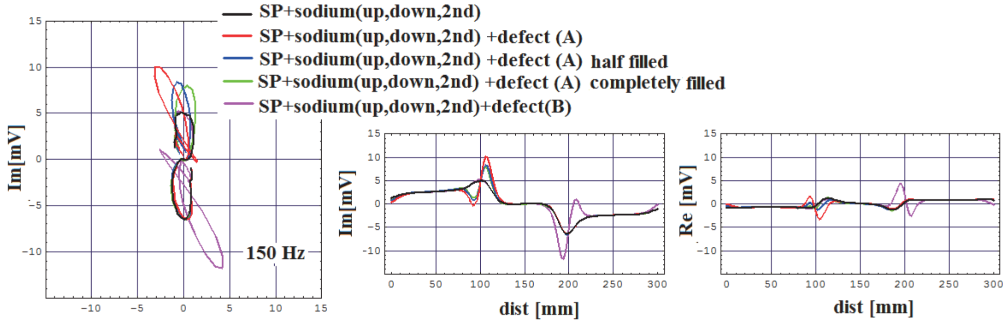


Fig.4. ECT signal at 150 from OD 50%tw position "A", "B" under large SP with 9 tubes

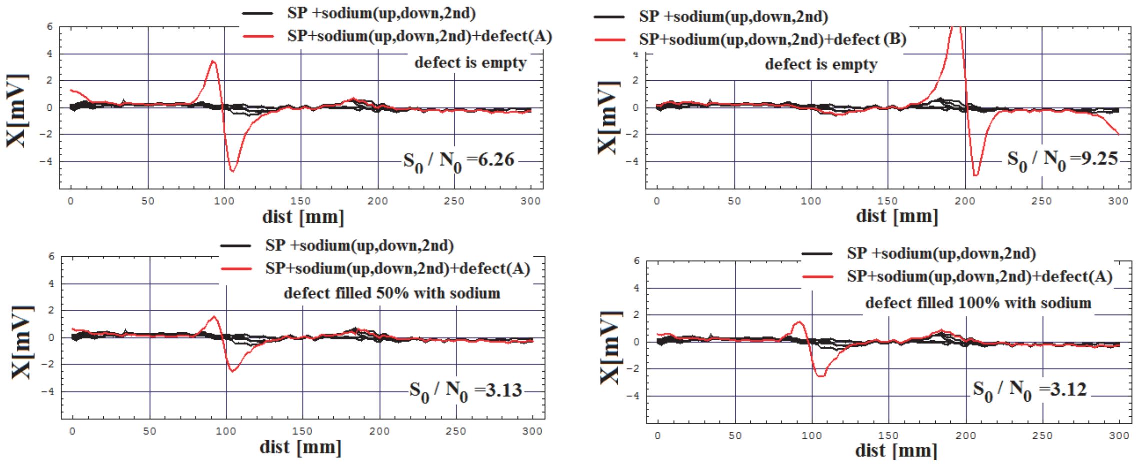


Fig. 5. Multi-frequency algorithms for 9 tubes-SP with sodium

Fig. 4 shows the simulated signal when defect position is "A" or "B" and the defect is either 50% or 100% filled with sodium at 150Hz. The large SP plate model has 9 SG tubes. By applying multi-frequency ECT algorithms, we cam detect defects filled partially 50% or even 100% with sodium in both position A and B with a signal/noise ratio larger by 3 (see Fig. 5).

In the papers, is at also developed a new enhanced algorithm, defined by the name “window multi-frequency” that is able to enhance the defect detection when there is sodium as shown in Fig. 6. Increased S/N ratios are obtained when window multi-frequency algorithm is determined directly from 3D FEM simulations of large SP with multiple SG tubes.

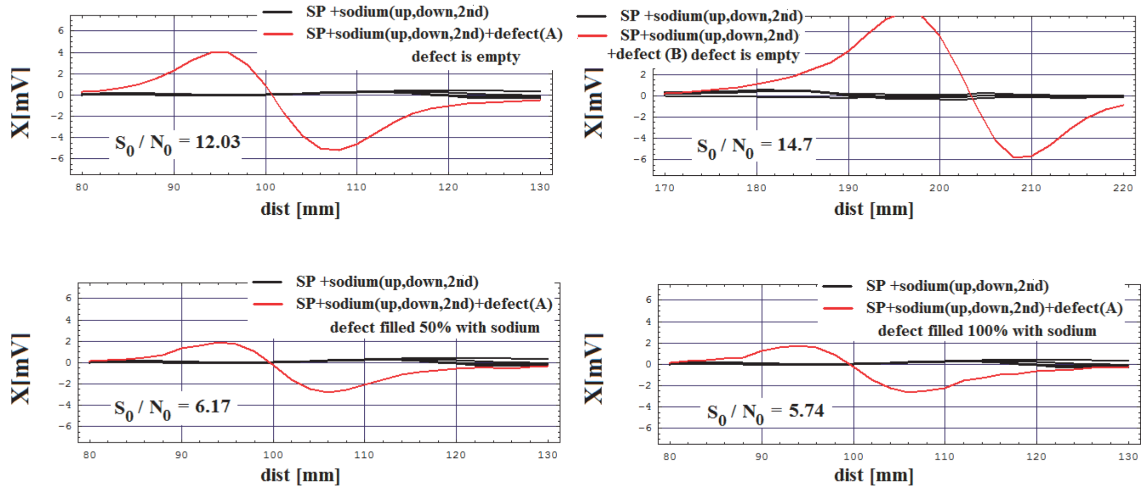


Fig. 6. "Window multi-frequency" algorithms for 9 tubes-SP with sodium

By applying the new multi-frequency technology the S/N ratio doubles from 3 to almost 6 independently from sodium noise level showing the effectiveness of the algorithm even when we do not know sodium forms sizes.

3. 評価結果

We showed the feasibility of applying multi-frequency algorithm to reduce electromagnetic noise from sodium structures. The papers show how to choose this algorithm among many options, and enhancing Signal/Noise ratio. Both multi-frequency and window multi-frequency algorithms were applied to models of small SP with one SG tube or large SP with nine SG tubes and with sodium.

Also it was developed and enhanced "window multi-frequency" algorithm which could provide a larger signal/noise ratio of defect detection under SP and in presence of sodium than classical multi-frequency algorithm. The algorithm feasibility was demonstrated using 3D numerical simulations based on FEM, even when the algorithm parameters were determined from a small SP model (1 SG tube) and then applied to the large SP model (9 SG tubes). However, the best results in multi-frequency algorithms were obtained when their parameters are determined directly from the full large SP model with 9 SG tubes.

本稿に関する投稿論文

[0-1] O. Mihalache, T. Yamaguchi, M. Ueda, "Computational Challenges in Numerical Simulations of ISI of Ferritic Steam Generator Tubes in Fast Breeder Reactors using Eddy Currents and Multi-frequency Algorithms", *E-Journal of Advanced Maintenance*, Vol. 3, No. 2, pp. 54-77, August, 2011.

[0-2] Ovidiu Mihalache, Toshihiko Yamaguchi, Masashi Ueda, "Multi-Frequencies ECT Algorithms for ISI of Ferromagnetic SG Tubes of FBR using FEM Simulations", *Proceedings of 15th International Symposium on Applied Electromagnetics and Mechanics,* 6-9 September 2011, Napoli, Italy, 2011 (accepted March 30, 2012, after per review for publication in *International Journal of Applied Electromagnetics and Mechanics*).