1-5 FEM Comparisons between RF-ECT Signals in Quasi-Static or Transient and Linear or Nonlinear Regimes for In-service Inspection of magnetic SG tubes in FBR

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Outline

During In-service-Inspection (ISI) of ferromagnetic steam generator (SG) tubes in fast breeder reactors (FBR), "remote field eddy current testing" (RF-ECT) is used to check for possible defects. In recent years our group has developed finite element method (FEM) simulation codes, aimed at speeding up design of RF-ECT probes while improving detection performance and reducing costs. In this work, we investigate the impact of two common approximations made in simulations: the quasi-static formulation of Maxwell equations, and the linear material properties of the tubes. To that aim we first evaluate the validity range of the simplified model, and then estimate the maximum error that can be expected against real world measurements.

1 Introduction

In the modelling of the RF-ECT technique [1], when applied to ISI of ferromagnetic SG tubes in FBR, the traditional approach is based on the quasi-static approximation of Maxwell equations at low frequency. Displacement currents are therefore neglected and, at low values of the excitation density current, the electromagnetic properties of the SG tube material are considered to be linear. This approach has been proven satisfactory at low probe speeds, and widely confirmed by both simulations and experimental measurements. As the ECT probe speed increases though, especially at higher density currents and for small defects of characteristic length size comparable to the eddy current wavelength, the validity of the linear and quasi-static approximations remains to be proven. To that aim we implemented a full time transient RF-ECT model and took into account the nonlinearity of the B-H virgin curve of the tubes.

2 FEM simulations fundamentals

2.1 Simulation codes

Two FEM simulation codes, based on different numerical approaches, have been used throughout. The first one is COMSOL [2], a general purpose FEM toolbox for solving physical problems formulated in differential equations. The second one has been developed in house purposely for the analysis of 2D axisymmetric RF-ECT problems [3]. Both codes have been used at every step as a mean to cross-check validate our results. In practice, the specialized JAEA code was always faster than the commercial-but-general-purpose one, the difference being as noticeable as 180x for some simulations.

2.2 Finite Elements domain

Fig.1 shows the basic axisymmetric layout for the simulations. In all of them we analyzed the presence of both inner and outer defects (ID and OD respectively) in a 380mm long, 12.1mm inner radius, and 3.75mm thick ferromagnetic SG tube. For each case, several defect geometries were evaluated, with widths of either 0.25mm (slit) or 5mm (circumferential defect) and depths of either 20 or 50% of wall thickness. The probe had two receiver coils 58mm far from the exciter and separated by 3mm; output signal was obtained as its difference. Probe stepping ranged from 0.01mm (38k calculation steps) to 1mm (380 steps), and the mesh size varied from 55k to 450k elements.

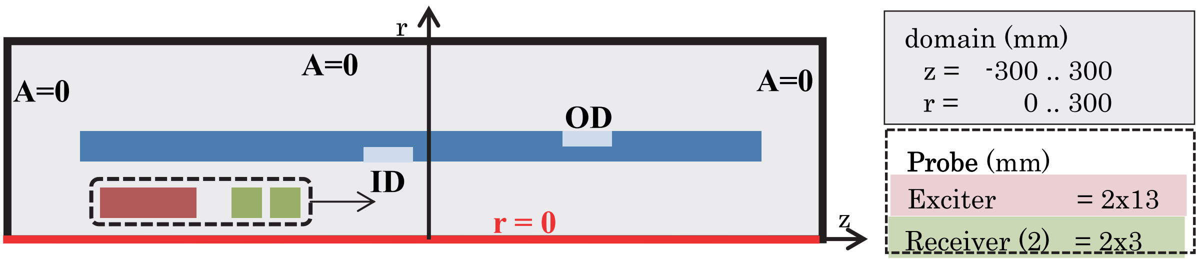
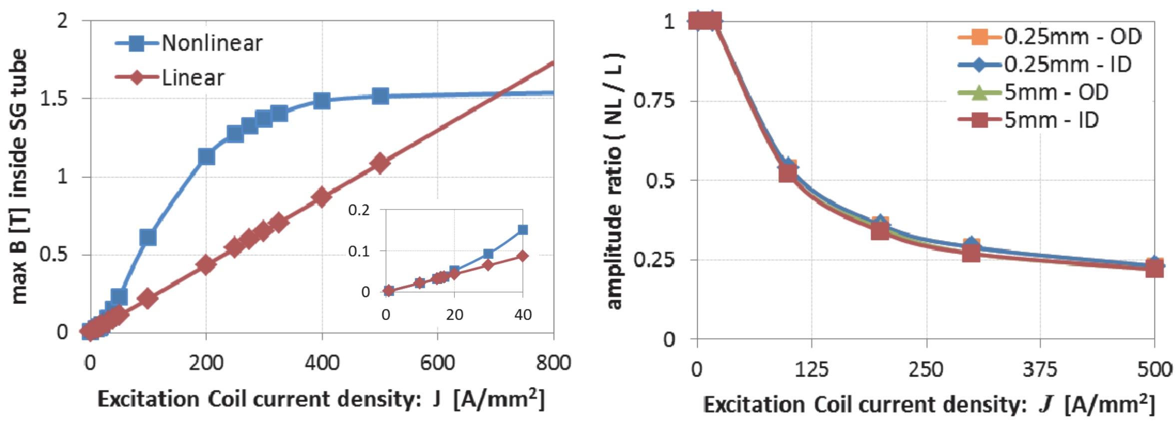


Fig. 1 : Schematic RF-ECT FEM simulations layout; *A* represents the magnetic vector potential magnitude

3 Results

3.1 *Influence of non-linear material properties*

The steam generator tubes of Monju FBR are made of a ferromagnetic 2.25Cr-1Mo steel, whose relative magnetic permeability (μ) depends on the field intensity. Fig.2a shows the effect of the rising μ up to 800 A/mm^2: on one hand the maximum magnetic flux density norm (B) increases versus the linear case, but on the other hand the whole field concentrates on the region near the tube inner surface (Fig.3), and that results in worse detection for both the circumferential slit and 5mm defect (Fig.2b). These results are consistent with theoretical predictions and by comparison with COMSOL validate the ability of the JAEA code to simulate the non-linear domain. However, it is important to note that during actual inspection with current techniques typical excitation currents are 1~3 A/mm^2, i.e. well within the linear domain, which extends up to 17 A/mm^2 at 150 Hz (Fig.2a).



(a) **(b)**

Fig.2: Effect of non-linear magnetic permeability on RF-ECT of Monju's SG tubes: **a)** Maximum magnetic flux density norm measured inside the SG tube with increasing excitation coil current density; non-linear

behavior shows up from ~17A/mm^2, and saturation at ~ 400 A/mm^2. **b)** RF-ECT simulations in Monju SG tubes for 50% w.t. deep defects of 0.25mm and 5mm widths.

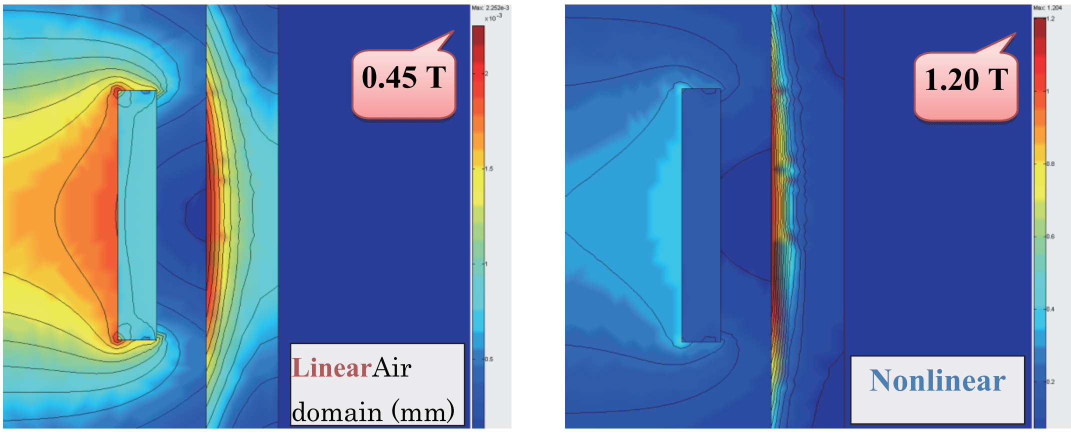


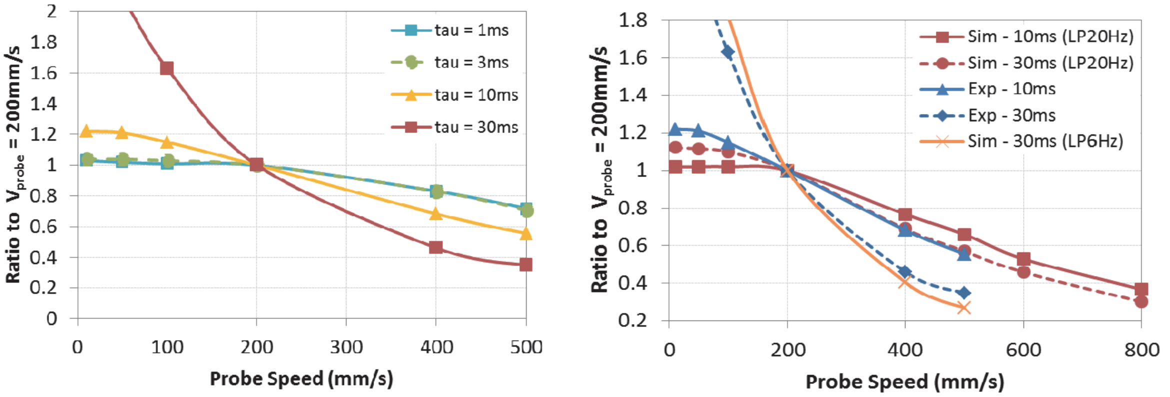
Fig.3: Magnetic flux density norm distribution during RF-ECT simulations: comparison between linear and non-liner magnetic permeability for an excitation current density of 200 A/mm^2

3.2 Influence of time transient analysis on probe speed effect

Typically during ISI of Monju SG tubes RF-ECT is performed at a probe speed of 200mm/s. However, because in the actual inspection the probe is pushed by compressed air into the highly bended tubes, it is believed that in some cases instantaneous speed can reach values as high as 800mm/s. Since the quasi-static approximation leads to results independent of probe speed, the possible impact of those brief accelerations in defect detection was analyzed in time-transient, including the lock-in amplifier used in our experimental setup.

Fig.4 summarizes our results. Experiments were carried out using a 1m long SG tube calibration sample, consisting of both inner and outer 5mm-wide and 20%w.t.-deep defects separated by 30cm. A motor-driven platform with precise and stable control of the probe speed up to 500 mm/s. is used instead of the actual ISI compressed air mechanism. Two effects can be observed on Fig.4a:

1. Defect amplitude measured over Lissajous diagrams decreases at higher speeds.
2. Higher lock-in amplifier time constants lead to greater variations with speed (for τ > 3ms).



(a) **(b)**

Fig.4: Effect of RF-ECT probe speed on 5mm wide 20% w.t. deep defect signal: **a)** signal amplitude variations for different speeds (10mm/s – 500mm/s) and lock-in amplifier time constant τ = 1 – 30ms; **b)** comparisons between simulation and experiment for a lock in amplifier time constant τ = 10 – 30ms.

As seen on Fig.4b both traits are adequately reproduced by simulations when using the standard lock-in amplifier time constant τ = 10ms, for which 70% of the defect signal could be lost at 800mm/s.

With τ = 30ms there were considerable quantitative differences between modeling and experiment. We believe these discrepancies arise from the low pass filter in the lock-in amplifier, which had a great impact on the simulations outcome. Indeed, it was enough to change the cut-off frequency to a lower value (20Hz → 6Hz) to closely match the experimental data.

It is finally worth noting that results were found to be independent on defect nature in additional runs for 0.25mm and 5mm wide - 50% w.t. deep defects.

4 Conclusions and perspectives

The present work estimates the maximum error in RF-ECT detection of inner/outer FBR SG tube defects at various probe speeds and simulation regimes.

The nonlinear magnetic permeability of the SG tubes had no influence on defect signals for coil excitation currents up to 17 A/mm^2, which is well above the standard level in actual ISI (1~3 A/mm^2).

By adopting a time-transient simulation approach we showed that sudden accelerations of RF-ECT probe speed up to 800 mm/s could result in as much as 70% of defect-signal drop. Results for the standard lock-in amplifier time-constant (τ = 10 ms) showed a reasonable agreement with experimental data, but further work will be needed to account for the discrepancies at larger τ.

Contribution article concerning to this report

[0] Daniel Garcia-Rodriguez, Ovidiu Mihalache, Masashi Ueda, "FEM Comparisons between RF-ECT Signals in Quasi-Static or Transient and Linear or Nonlinear Regimes. ECT Probe Speed Effect for In-service Inspection of Ferromagnetic SG tubes in FBR, *Proceedings of 15th International Symposium on Applied Electromagnetics and Mechanics,* 6-9 September 2011, Napoli, Italy, 2011 (accepted March 30, 2012, after peer review for publication in *International Journal of Applied Electromagnetics and Mechanics*).

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