Development of methods for modeling complex defects in eddy current non-destructive evaluation

Eddy current non-destructive testing (EC-NDT) is one of the primary methods used for inspecting steam generator tubes in pressurized water nuclear reactors. Among the degradation mechanisms that can affect these components, stress corrosion cracking can lead to complex crack morphologies whose detection and characterization represent a major challenge for the safety and availability of nuclear facilities. However, the relationship between crack morphology and the electromagnetic response measured by eddy current sensors remains difficult to establish. Most studies in the literature base their analysis on canonical defects with simple geometries, such as electro-discharge-machined rectangular notches, for the sake of simplification, whose representativeness with respect to real cracks remains limited. Furthermore, uncertainties affecting both defect geometry and experimental measurements further complicate signal interpretation.

The objective of this thesis is to develop a more representative modeling approach for realistic defects, in order to establish a less idealized framework that quantitatively relates EC-NDT signals to defect morphology.

First, a high-fidelity finite element model of the inspection process is developed to account for realistic cracks, either reconstructed from tomographic data or defined parametrically by the user. An automated methodology for inserting these complex geometries is proposed and experimentally validated on several industrial configurations for which X-ray tomography data paired with corresponding EC-NDT signals are available. The results obtained highlight the significant influence of real crack morphology on the measured signal and demonstrate the limitations of the canonical models conventionally used.

Second, a geometric reduction procedure, called UCE (Unification, Convolution, Equivalence), is proposed to represent a set of realistic cracks by an equivalent elliptical defect. This representation enables parametric and probabilistic studies to be carried out while preserving the essential EC-NDT indicators of the defects. It thus becomes possible to address the problem within a Verification, Validation and Uncertainty Quantification (VVUQ) framework using low-dimensional inputs/outputs. Gaussian process metamodels are constructed from finite element simulations and used to perform global sensitivity analyses based on Pearson and Spearman coefficients as well as Sobol indices. The results reveal the dominant physical mechanisms governing the EC-NDT indicators and expose a coherent underlying structure of the problem.

Finally, a Bayesian inversion methodology is developed to probabilistically estimate the geometric characteristics of defects from measured signals. This approach makes it possible to explicitly account for the various sources of uncertainty associated with the modeling, the geometric simplification, and the experimental measurements, while addressing the ill-posed nature of the inverse problem.