Finite Element Modeling of Eddy Current Probes for CANDU® Fuel Channel Inspection

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Abstract

As shown in Figure 1, CANDU® reactor fuel bundles are immersed in a heat transport coolant within a Pressure Tube (PT). Surrounding the PT is a gas-filled Calandria Tube (CT), which thermally isolates the PT from the moderator surrounding the fuel channels. Four annulus spacers separate the PT from the CT to prevent hydride blistering of the PT, which could occur under contact conditions. The reactor's fission reaction rate may be controlled from a Liquid Injection Shutdown System (LISS), which injects neutron poison into the moderator surrounding the fuel channels. The injection nozzles are just exterior to the calandria tubes. A non-destructive technique is necessary to accurately measure the PT-CT gap.

A Pulsed Eddy Current (PEC) probe, which uses the transient response to a pulse-train voltage to detect and measure CT-LISS nozzle proximity, is being developed for in-reactor inspection. PEC generates a spectrum of discrete frequencies, allowing the simultaneous measurements from a range of depths that is unachievable from conventional eddy current, which only uses a limited number of frequencies obtained from separate time harmonic excitations.

As shown in Figure 2, the prototype probe consists of a drive and pickup coil. The drive coil is excited by an external power supply, while the pickup coil is electromagnetically coupled to the drive coil via the magnetic field induced in the fuel channel. Two COMSOL Multiphysics® models were created using the "Magnetic Fields (mf)" interface in the AC/DC Module. The first model approximated the geometry of the fuel channel as parallel plates (to compare against analytic solutions) and the second reflected the true geometry. The PT-CT gap response was found by placing a stack of CTs above the PT and running a parameter sweep to set a particular CT as being made of metal or air. Similarly, the coils were divided into fifths and were stacked. These "fifth-coils" were connected in series via the "Electronic Circuits (cir)" interface and a parameter sweep was used to electrically connect the fifth-coils to a pull down or pull up resistor. In this fashion, the distance between the coils and the fuel channel could be changed via a parameter sweep. Conventional and PEC technologies will be compared to evaluate their relative strengths and weaknesses.

As shown in Figure 3, the voltage responses of the pickup coil for conventional EC are dependent on the frequency of excitation in the drive coil and as expected, asymptotically approach a steady state value as the PT/CT gap increases. One also observes that the curvature

of the pipe effectively increases the impedance of the eddy currents and thereby results in a lower induced voltage in the pickup coils as compared to a planar geometry.

A limitation of conventional EC technology is that the coil responses are heavily dependent on the skin depth within the conducting test piece. Results will be validated against analytical model results and experimental data. The transient response using PEC is currently under development and eventually the efficacy of both EC techniques will be compared.

Reference

[1] S.T. Craig, T.W. Krause, B.V Luloff and J.J. Schankula, “Eddy current measurements of remote tube positions in CANDU reactors,” in 16th World Conference on Nondestructive Testing, Palais des Congrès, Montreal, Canada, 2004, Aug. 30-Sept. 3.

[2] S. Shokralla, T. W. Krause and J. Morelli, “Surface profiling with high density eddy current non-destructive examination of data,” NDT&E International, vol. 62, March 2014.

Figures used in the abstract

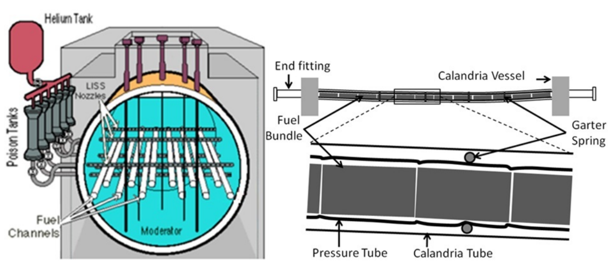

Figure 1: A schematic of a CANDU® fuel channel assembly (left) [1] and a schematic of an individual fuel channel (right) [2].

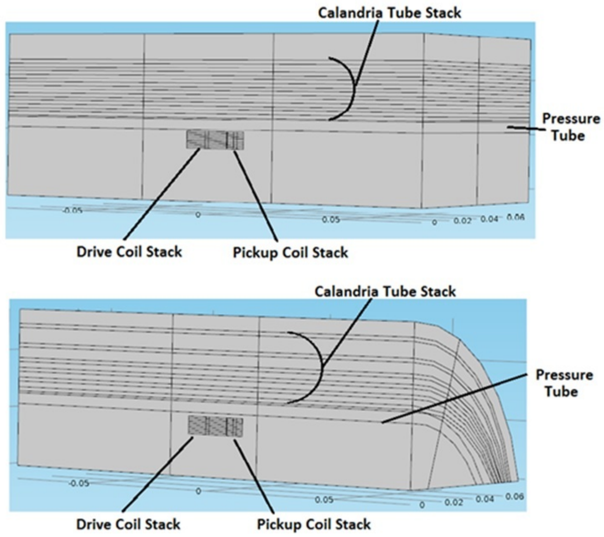

Figure 2: COMSOL models of the fuel channel approximated as planar sheets (top) and the true geometry (bottom).

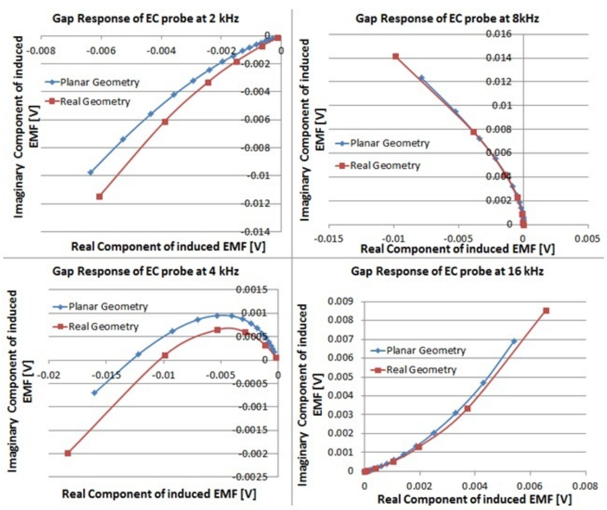

Figure 3: A plot of the pickup coil responses due to a 10 V amplitude time-harmonic excitation of varying frequencies to simulate the PT-CT gap response of a conventional EC probe. Note that the origin corresponds to an infinite PT-CT gap (i.e. no CT).