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Surface profiling with high density eddy current non-destructive examination data

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ABSTRACT

The pressure tubes (PT) in CANDU (CANada Deuterium Uranium) reactors undergo creep induced deformation due to operating pressure, temperature and radiation conditions. While global deformation of the tube in the form of elongation and diametral creep is well characterized and monitored by station inspection systems, local PT deformation and the presence of inner surface artifacts due to wear are not as directly monitored, but can still provide additional information of fuel channel condition. A surface profiling technique for monitoring local deformation and identification of surface wear using an eddy current probe mounted in a small (50 mm × 25 mm) planar probe body is presented. The sensitivity of the eddy current probe to small lift-off variations combined with high density C-Scan information is used to extract information on smoothly varying local deformation as well as monitor more significant wear on the inner surface of pressure tubes. Vector separation of components permits independent identification of axial and circumferential surface features. Analysis of this data can be used to characterize local PT deformation due to constrictions at fuel bundle ends and loaded garter spring spacers, as well as identify areas where shallow mechanical wear has occurred. Examples of the features that may be identified are presented.

1. Introduction

Eddy current inspection is a key non-destructive examination (NDE) process employed towards characterization of defects in conductive materials. Piping and heat exchanger (including steam generator) inspections are common applications of eddy current non-destructive examination of nuclear power plants [1–3]. Specific to CANDU (CANada Deuterium Uranium) reactors, however, eddy current examination has been used towards a number of non-standard fuel channel related applications with regard to the geometry identified in Fig. 1. These include identification of the presence and proximity of remote structures to fuel channels [4], detection of spacers, which maintain gap between pressure and calandria tubes [5] and direct measurement of gap between pressure tube and calandria tube [6].

There are two standard ways in which eddy current data is interrogated. The first is by examination of the Lissajous curve, which provides the resistance and inductive reactance recorded by an eddy current receive probe during data acquisition. The second is through examination of the C-Scan, in which the component orthogonal to the direction of lift-off is plotted as a function of measurement location (points on a two-dimensional grid).

There are many examples of employing high data density towards eddy current C-Scan imaging. Imaged data can either be minimally conditioned [7,8], or alternatively, a significant degree of signal and image processing can be employed [9–12].

For flaw detection applications, examination of lift-off in eddy current data is normally avoided and is considered a source of noise [13,14]. The application of paint and metal deposition thickness measurement is well known. But its potential for surface profiling is not as well recognized [15]. For the particular circumstance where a large planar probe body is present, lift-off may be utilized to provide additional information that would be available if the probe maintains surface following or surface riding characteristics.

This study shows how high eddy current data-density, basic knowledge of mechanical interaction between the probe and test-piece, and lift-off response can be employed towards profiling a test-piece surface to a high degree of precision. The technique to be described in detail is simple to implement, relying on a computation of partial derivatives with respect to variables whose direction represents orthogonal image axes (an image processing building block [16,17]). Ease of technique implementation is in contrast to more elaborate techniques for analysis of eddy current

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data, including neural network implementation and wavelet transformation [11,18–20].

The technique will be compared against another currently employed ultrasound based method for detection of spacer and pressure tube artefact locations, important activities in ensuring integrity of CANDU nuclear reactor fuel channels.

2. Inspection requirement

Fuel channels are a critical component of CANDU power plants. They carry the fuel bundles as they are transported across the core of the reactor, whose configuration is shown in the top portion of Fig. 1. Each fuel channel is made up of a 6 m long pressure tube (which directly houses twelve 0.5 m long fuel bundles) and a surrounding calandria tube. The pressure tube and calandria tube are separated by four spacers, which are manufactured from a square cross-section Zr-alloy wire formed into a tight helix. Further details of these fuel channel components are shown as a magnification in Fig. 1.

Fuel channels are periodically inspected in order to characterize the presence and status of different degradation mechanisms, thereby meeting their safety and licensing requirements [21]. This is performed by insertion of an inspection head along the length of the fuel channel during reactor shutdown periods. A number of different degradation mechanisms and pressure tube artefacts can be identified by various NDE methods (including eddy current). These include the following:

- *Localized deformation due to garter spring spacer loading*: Garter spring spacers serve the purpose of ensuring separation between the pressure tube and relatively cool calandria tube. Loading is therefore induced on the pressure tube by the spacer and supporting calandria tube. This leaves the pressure tube slightly ovalized in the vicinity of the spacer.
- *Constrictions*: Locations at fuel bundle ends where radiation induced creep is less due to lower flux densities relative to the centre of fuel bundle locations. This leaves the diameter of the pressure tube at a constriction smaller than for neighbouring regions, while forming a pressure tube wall protrusion on the order of 0.1 mm.
- *Mechanical wear marks*: Mechanical interaction between fuel bundles moving across the fuel channel and the supporting pressure tube can induce wear on the pressure tube. Mechanical wear marks indicate this repeated interaction. The wear marks have nominal depth in the range 50–100 μm.

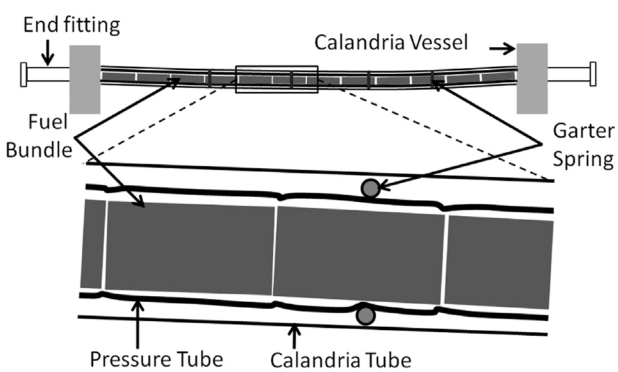

Fig. 1. Configuration of a CANDU fuel channel.

3. Measurement technique

Eddy current data is gathered helically by an eddy current probe mounted on an inspection head that is driven axially and rotationally along the pressure tube (Fig. 2). The axial pitch of the probe's helical travel is small (1 mm), compared to its rotational travel, allowing for approximation of the helical trajectory as a series of circular trajectories separated axially by 1 mm.

The eddy current probe is mounted on the inspection head, with transmit and receive coils situated along the axial direction of the pressure tube, when the inspection head is installed in-channel. The probe is spring loaded such that it rides the surface of the pressure tube. In the event that the probe makes contact with an obstruction embedded in the pressure tube interior, as shown in Fig. 2, limited motion with two degrees of freedom is also permitted: about the inspection head rotary direction of motion (forward and backward tilt), and away from the pressure tube surface in the direction of spring force.

The eddy current signals are generated and received via an Olympus NDT Multi-scan MS5800 eddy current instrument. Custom software is employed to view acquired signals in real time as well as post-acquisition. Eddy current signals are acquired on multiple frequencies, which include 8 kHz and 16 kHz. Unadjusted raw measurements have units mV.

4. Lift-off location extraction

We represent the acquired eddy current data set as a complex valued function $f(x, y)$ mapping rotational and axial values (x and y) to the complex plane, $\mathcal{C}$. We use $\mathcal{C}$ to represent the domain where

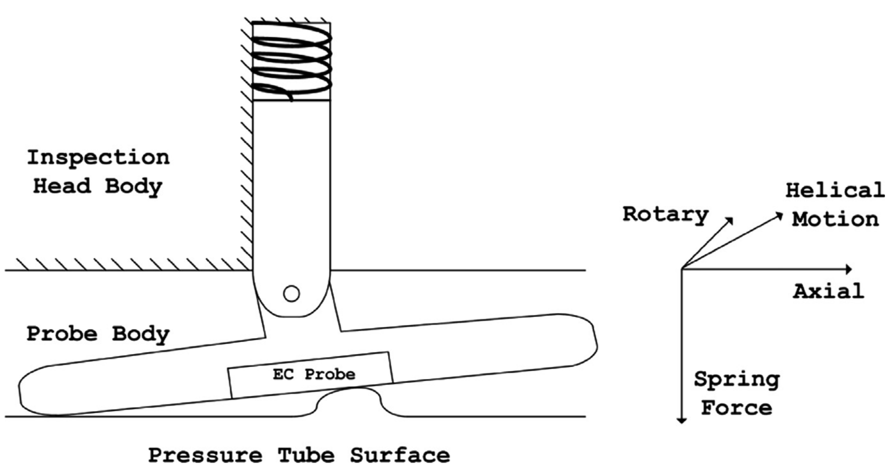

Fig. 2. Eddy current (EC) probe riding over exaggerated pressure tube protrusion.