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RFEC Inspection for Coaxial CANDU Fuel Channel Tubes

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ABSTRACT

Remote field eddy current (RFEC) inspection is a nondestructive through-wall examination technique based on the diffusion of electromagnetic energy from exciter to sensor coils in a pipe. This characteristic is of interest as a potential nondestructive technique for inspecting tube-in-tube configurations in a Canadian Deuterium Uranium (CANDU) reactor where axially positioned garter spring spacers separate the nominally coaxial pressure and calandria tubes. We report tests of RFEC to inspect the garter spring and the gap between a nonmagnetic Zr-2.5%Nb pressure tube and a Zircaloy-2 calandria tube from a CANDU fuel channel. Our results show that RFEC is a promising integrity evaluation tool for coaxial CANDU fuel channel tubes.

INTRODUCTION

The remote field eddy current (RFEC) inspection technique is a nondestructive method which uses through wall transmission to inspect pipes and tubes from the inside. The through wall nature of the technique allows external and internal defects to be detected with approximately equal sensitivity. The RFEC tool uses a relatively large internal solenoidal exciter coil driven with low frequency AC. A detector, or circumferential array of detector coils, is placed near the inside of the pipe wall, but axially displaced from the exciter by about two pipe diameters, depending on the material properties of the pipe wall. Two distinct coupling paths exist between the exciter and the detector coils. The direct path, inside the tube, is attenuated rapidly by circumferential eddy currents induced in the tube wall. The indirect coupling path originates in the exciter fields which diffuse radially outward through the wall. At the outer wall, the field spreads rapidly along the tube with little further attenuation. These fields re-diffuse back through the pipe wall and are the dominant field inside the tube at remote field spacing. Anomalies anywhere in the indirect path cause changes in the magnitude and phase of the received signal and can therefore be used to detect defects [1, 2]. RFEC probes are already used for commercial inspection of heat exchanger tubes. There are several other important potential applications for RFEC techniques including the inspection of water and gas distribution lines. These have elbows and tees which are difficult for any other tool to negotiate.

The core of a Canadian Deuterium Uranium (CANDU) reactor includes 6 m long horizontal pressure tubes containing the nuclear fuel bundles. Concentric with these tubes are calandria tubes with an annular gap between them. Axially positioned garter spring spacers separate the calandria and pressure tubes. Because of unequal mechanical and irradiation-induced creep rate between the tubes, the garter spring moves from its design location and the gap changes with time. The pressure tubes finally contact the calandria tubes which induces pressure tube failure due to metallurgical causes [3]. Therefore, nondestructive garter spring location and gap determination are essential preliminary steps before repositioning the spacers to assure the integrity of fuel channels. However, the gap is gas filled so that ultrasonic testing is not applicable.

In this study, we have evaluated experimentally the position of the garter spring and size of the gap between a nonmagnetic Zr-2.5%Nb pressure tube and a Zircaloy-2 calandria tube from a CANDU fuel channel using the emerging nondestructive RFEC technique.

EXPERIMENT

A simplified drawing of the CANDU coaxial tubes is shown in figure 1. This was used to test nondestructive garter spring location by the RFEC technique. The relatively large exciter coil is inside the pressure tube. A small spot coil type of receiver is positioned close to the inside of the pipe wall and arranged to sense either axial or radial field components. Based on pull-away tests at frequencies of 3 to 6 kHz, it was found that an axial separation of 1.5 pressure tube inner diameters between exciter and sensor coils was enough to ensure RFEC coupling. The outer diameter and thickness of the Zr-2.5%Nb pressure tube are 114 mm and 4.5 mm and the inner diameter and thickness of Zircaloy-2 calandria tube are 130 mm and 1.5 mm, respectively. The RFEC inspection pig composed of exciter and sensor coils was moved inside the tubes to detect garter springs nondestructively. The overall scan length was 300 mm and a sufficient margin from either end of the tubes was maintained to avoid end effects [4].

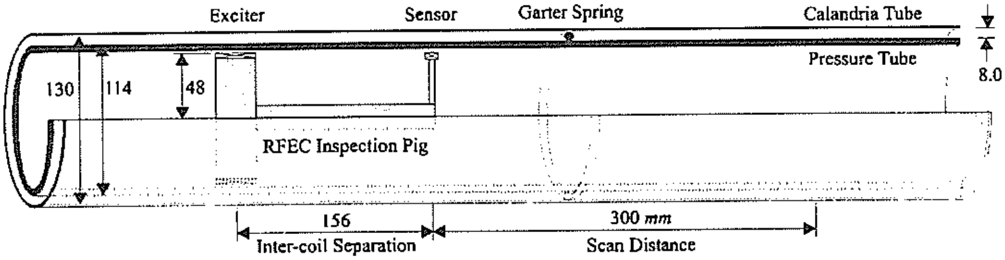

Figure 1. A simplified drawing for nondestructive garter spring location in CANDU coaxial fuel channel tubes.

The experimental apparatus was typical to others for RFEC measurement, as in our previous publication [5], and a tube-in-tilted tube system was used for nondestructive sizing of the gap variation caused by sagging in a CANDU nuclear fuel channel. A function generator sinusoidally modulates the output of a bipolar power supply acting as a power amplifier operating in voltage mode. The power amplifier was adjusted to generate a current of 0.13 A at 3 to 6 kHz. The output signal was sent to the exciter coil and also to a Stanford Research Systems SR 530 lock-in amplifier through a reference resister. The exciter coil consists of 50 turns of 20 AWG copper wire wound on a 96 ± 1 mm diameter form. The internal RFEC detector coil can be mounted to sense the axial or radial B field components.

The detector coil has 5000 turns of 47 AWG copper wire. Its inner and outer diameters are 5 ± 0.5 mm and 8 ± 0.5 mm, respectively. Its small area allows relatively high-resolution measurements of the RFEC amplitudes and phases which are fed into a control PC through the lock-in amplifier.

At these high frequencies, noise problems were easily controlled by careful grounding of the circuits to a common point and by shielding all measurement cables. The axial displacement of the RFEC probe was measured using a shaft encoder and recorded by a PC. A Pascal program controls the RFEC data acquisition process and records such measured data as axial position, amplitude and phase of the RFEC signal.

RESULTS AND DISCUSSION

Voltage plane polar plot (VPPP)

The measured RFEC signal was processed to obtain the voltage plane polar plot (VPPP), recognized as a standard representation of RFEC data for analysis [6]. The VPPP is an effective representation of RFEC signals because the amplitude and phase of the normalized signal trace are displayed on a polar plot. It differs significantly from the impedance plane display used for conventional eddy current methods where the real and imaginary parts of the detected signal are plotted. The interpretation of RFEC signals relies on normalizing the data, rather than on calibration samples. The unperturbed RFEC signal at a clean full-wall position is chosen as a reference and used to normalize RFEC scan data for VPPPs. Therefore, this reference point is always located at the (1, 0) position on the VPPP and is usually called the full-wall position. Deviations from the full-wall baseline signal can be analyzed using calculated reference traces for different anomalies.

Remote field gap evaluation at a tube-in-tilted-tube system

The tube-in-tilted-tube arrangement was used to evaluate the gap change due to sagging in the CANDU fuel channel. A new RFEC parameter, the distance between each RFEC trace

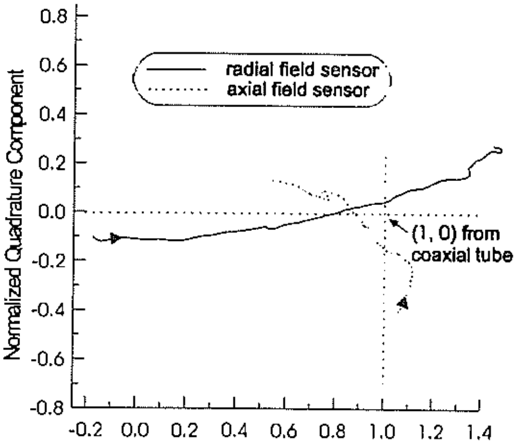

Figure 2. VPPPs of radial and axial field sensors at 4 kHz for a tube-in-tilted tube system.

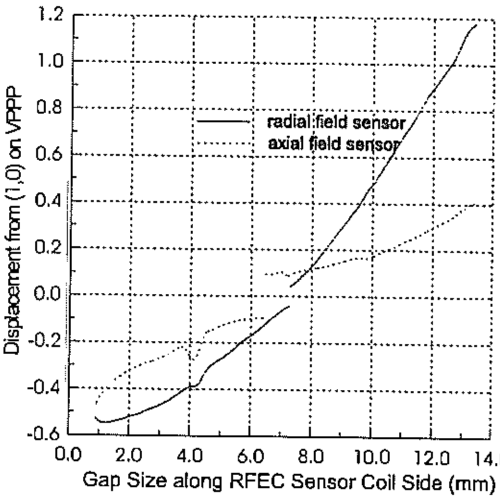

Figure 3. Gap size evaluation using displacement from (1, 0) on the VPPP at 4 kHz.

at a specific gap position on the VPPP and the VPPP (1, 0) position, was derived to evaluate the gap using the RFEC technique. VPPPs for gaps in tube-in-tilted tubes are shown in figure 2 for radial and axial field detectors at a frequency of 4 kHz. Because the RFEC signals from the asymmetric tube-in-tilted tube arrangement were normalized by those from the axisymmetric coaxial tube arrangement, the (1, 0) positions deviate slightly from the curves on the VPPP [5]. Figure 3 shows the gap dependence on the displacement from the VPPP (1, 0) position for the radial and axial sensor coils. The transient anomalies on figures 2 and 3, particularly notable for the axial field sensor, come from previously machined axial slots in the pressure tube used to study the influence of these anomalies on RFEC signals. The discontinuities of the curves in figure 3 are due to the choice of normalization signal from the coaxial tubes. The experimental relationship for gap evaluation with the displacement on VPPPs is very good at 4 kHz and the radial field sensor has better gap sensitivity than the axial sensor as in the average slope of figure 3.

Nondestructive garter spring location in the CANDU fuel channel

The centralizing spacers, more commonly referred to as garter springs, separate the calandria and pressure tubes in CANDU nuclear fuel channels. Running through the center of the garter spring is a girdle wire which has its ends resistance welded to each other. This maintains the circular shape of the spring assembly. Pressure tubes and springs are installed on site as part of the construction program. Once springs are installed there is no possible access to them by any other means than by cutting into the pressure or calandria tubes. The nondestructive location of garter springs is important because of heat economy and the uncertain effects on pressure tube life [7]. Eddy current, real-time radiography, acoustic emission, ultrasonics and infrared detection were all methods capable of finding springs. An eddy current module with send/receive coils stood out currently as the method most suited to the needs. This was adopted for the present garter spring location module in the channel inspection and gauging apparatus for reactors (CIGAR) and the spacer location and repositioning (SLAR) family [8, 9].

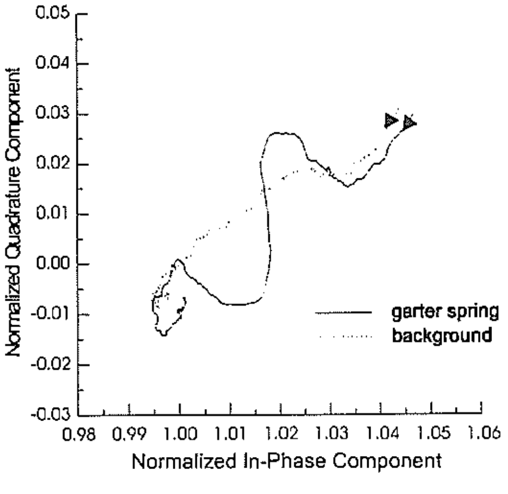

Figure 4. VPPP signatures of a garter spring and background using a radial field sensor at 4 kHz.

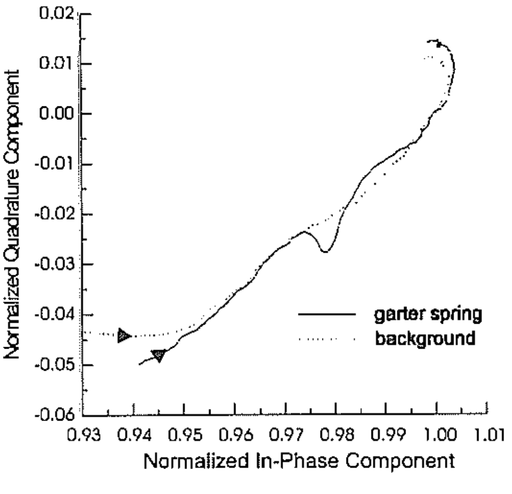

Figure 5. VPPP signatures of a garter spring and background using an axial field sensor at 4 kHz.

We applied the nondestructive RFEC principle to locate garter springs in the fuel channel tubes because RFEC has the unique characteristic of through-wall transmission. Because the old type of a garter spring has a loose fit over a pressure tube, the way that the garter spring is placed over the pressure tube influences its detectability by the RFEC technique. Even though the signal from the presence of garter springs is relatively weak, this research shows that they can be evaluated by radial and axial field sensors at frequencies of 3 to 5 kHz. Figure 4 shows the RFEC signatures of a garter spring picked up by a radial field sensor and figure 5 shows those from an axial field sensor at 4 kHz. The radial sensor gives a clearer and bigger garter spring signature than the axial sensor.

The effects of slow drift in the RFEC signal in the figures are caused by general variations in the magnetic properties, wall thickness at the tubes and/or fill factor between the sensor and the tube surface. These fluctuations are removed by subtracting a moving window average from the input samples. As a new data sample arrives, the window advances. The sum, and hence the average, of the fixed size window is recalculated by adding the new sample to the sum and subtracting the oldest sample. The new average is then subtracted from the sample in the middle of the window. The result is a signal data stream with attenuated low frequency or long wavelength components [10]. The processed RFEC signatures for a garter spring and background are shown in figures 6 and 7 after moving window averaging. The garter spring signatures become clearer with moving window averaging because of the removal of the slow drift in signal level and the contraction of background noise. The moving window size was composed of 99 data samples, equivalent to 50 mm. The radial field sensor gives better sensitivity than the axial field sensor, as evident from figures 4 and 5.

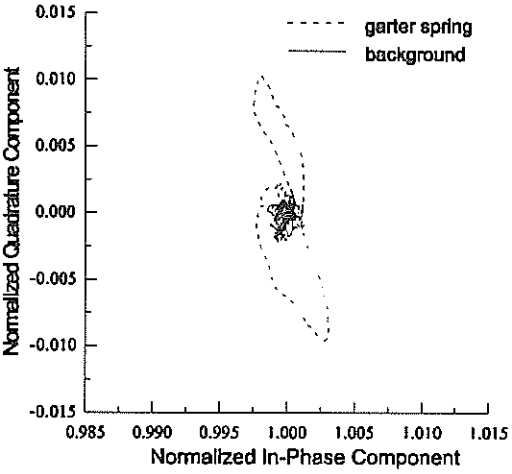

Figure 6. VPPP signatures of a garter spring and background using a radial field sensor at 4 kHz after moving window averaging.

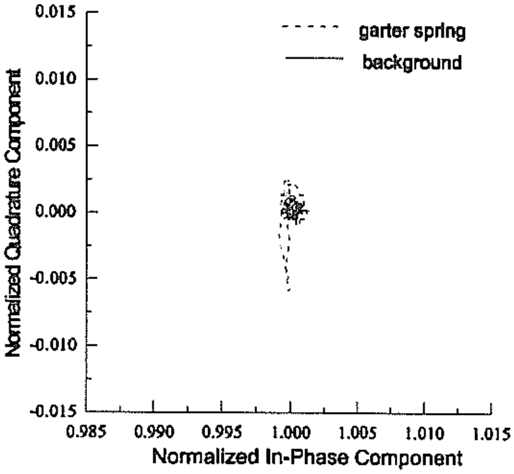

Figure 7. VPPP signatures of a garter spring and background using an axial field sensor at 4 kHz after moving window averaging.

Challenge to broken garter spring location in the CANDU fuel channel

An electrical current is induced in the girdle wire of a garter spring and can be detected by the standard module used for garter spring location. In reactors with overlapped (as opposed to welded) girdle wires, oxidation can impede the current flow after a short period of

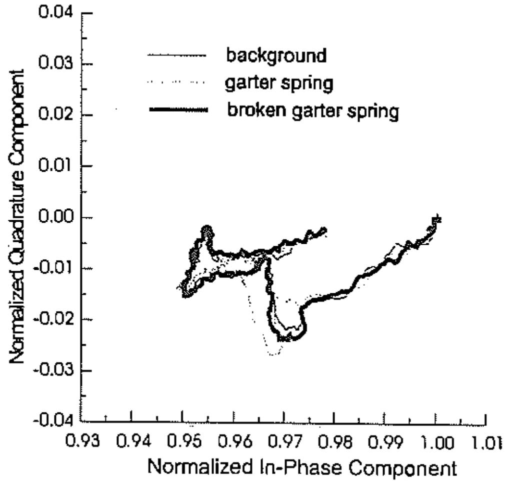

Figure 8. VPPPs of a garter spring and a broken garter spring using a radial field sensor at 3 kHz.

hot operation, reducing the system's ability to detect garter springs with eddy current techniques. Springs by themselves, or springs with broken girdle wires produce almost no signal at all [7]. A specialized ultrasonic probe has been developed to detect garter springs by searching for the low amplitude, repetitive signal of the spring's helical coil [11]. The RFEC technique based on through-wall transmission was tested to evaluate broken garter spring detection. Figure 8 shows the signature of a garter spring with a broken girdle wire using a radial field sensor at 3 kHz. The tiny change in the RFEC signature comes from the transmission thickness change in the presence of a broken garter spring not from the induced eddy current in the girdle wire.

An experiment with an aluminum ring and a broken one was tried to determine whether the RFEC signal came from the energy transmission thickness change over a RFEC sensor and/or the presence of induced eddy currents in the ring. The RFEC signatures may be from both induced eddy current and thickness change with the Al ring but only from thickness change with the broken Al ring. The Al ring was machined to fit between the tubes with an inner diameter of 116 mm, an outer diameter of 128 mm and a thickness of 4.7 mm. The rectangular cross section of the ring was 6 mm x 4.7 mm. Figure 9 shows the VPPP signatures of an Al ring and a broken one using a radial field sensor at 3 kHz. The induced eddy current in the ring has a much bigger influence on the RFEC signature than the energy

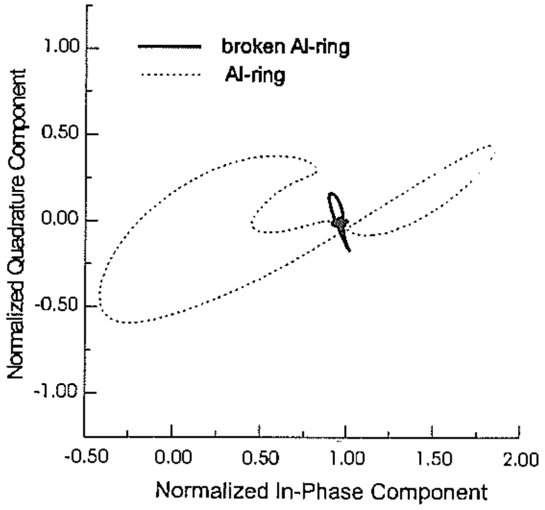

Figure 9. VPPP signatures of an Al-ring and a broken Al-ring using a radial field sensor at 3 kHz.

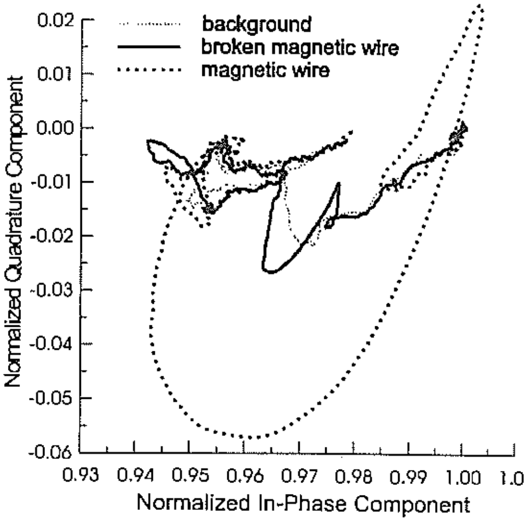

Figure 10. VPPPs of a magnetic wire ring and a broken magnetic wire ring using a radial field sensor at 3 kHz.

transmission thickness change does in the nonmagnetic tube with the nonmagnetic aluminum ring. This explains why it is difficult to detect the broken garter spring, as shown in figure 8. However, the RFEC contribution induced in the transmission thickness change might give the possibility of RFEC detection of broken garter springs, unlike the standard eddy current module. The development of both improved RFEC measurement and better signal processing methods is of course needed.

Figure 10 shows RFEC signatures of a magnetic wire detected by a radial field sensor at 3 kHz. The electrically connected and broken arrangements of the magnetic wire ring have the same dimensions as the girdle wire in the garter spring. A magnetic wire gives a much bigger RFEC signature than the garter springs. The electrically broken magnetic wire can also be identified more clearly than the broken garter spring, due to the presence of an induced magnetic field at the magnetic wire.

CONCLUSIONS

The garter spring and the gap in the CANDU fuel channel have been evaluated experimentally by using the RFEC principle. The gap in a tube-in-tilted tube system was correlated with a new RFEC parameter derived from the VPPP. Distinct RFEC signatures of garter springs were also obtained with axial and radial field sensors after moving window averaging, which removes the slow drift in RFEC signal. Radial RFEC sensor coils give better gap and garter spring detection sensitivities than axial coils. A broken garter spring shows a tiny RFEC signature which comes from the transmission thickness change. A magnetic wire with the same dimension as a garter spring gives a much bigger RFEC signature than a garter spring does because of the induced magnetic field at the wire. The RFEC signature was due to both induced eddy current and thickness changes with the Al ring but only from a thickness change with the broken Al ring. This offers the possibility of detecting a broken garter spring with an improved RFEC measurement and superior signal processing techniques. Our results show that the RFEC technique using through-wall transmission characteristics is a promising tool for gap determination and garter spring location for CANDU nuclear fuel channels.

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