INNER EDDY CURRENT TRANSDUCER WITH ROTATING MAGNETIC FIELD APPLICATION TO EXAMINATION OF FUEL CHANNELS OF PHWR NUCLEAR POWER PLANT

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Abstract:

For the control of fuel channels of PHWR CANDU type, a novel type of rotating magnetic field eddy current transducer was developed, as well as the afferent electronic equipment. So the presence of the discontinuities on external and internal surface of the tubes can be emphasized. A numerical code for the solving of the forward problem was developed.

INTRODUCTION

A critical part of pressurized heavy water reactor (PHWR) CANDU 600MW(e) type Nuclear Power Plant is the calandria tube made of austenitic steel, two integral end shields (also made of austenitic stainless steel) with carbon steel shielding balls each, horizontally penetrated by 380 lattice tubes, 380 Zircaloy-2.5 calandria tubes joining the lattice tubes at each position in the lattice and 380 fuel channel assemblies mounted within these lattice sites [1].

The fuel channel assemblies (Figure 1) consists of Zirconium –2.5%Niobium alloy pressure tubes (6.3m long x 105mm nominal bore x 4.16mm minimum wall thickness to house fuel and pressurized D_2O coolant); AISI type 403 stainless end fittings, with type 410 stainless steel liners; 4 garter springs tube spacers to support each pressure tube within its calandria tube; positioning assemblies for each end fitting; shield plugs for every end fitting to minimize neutron leakage from the fuel channel and to provide axial support to the column of 12 fuel bundles; removable closure plugs to seal each end of the fuel channels and to enable access for refueling by the fuelling machine; feeder connections.

The calandria is filled with D_2O, which moderates the fast neutrons, that allows chain reaction to take place. The heat in the fission reactor within the fuel is transferred to the pressurized D_2O coolant, which is pumped through the fuel channels. The annular space between the pressure tube and calandria tube provides thermal insulation between the hot heat transport system coolant and the cool moderator. Nominal inlet pressure of coolant is 9.8MN/m^2, the inlet temperature is 249^{0}C and the outlet temperature is 293^{0}C. The full power refueling requirements for CANDU 600MW(e) reactors involve replacing about 110 fuel bundles per week, which entails refueling 14 fuel channels per week.

Conforming to [2], at outage, a number of fuel channels are tested using nondestructive methods such as visual methods with video cameras, ultrasound and eddy current techniques using an inspection head that it is positioned with the aid of the refueling machine. The inspection head is pushed inside the pressure tube.

The inspection, is used to extract information about [3]:

- the position and tilt of garter springs [4]

- cracks on internal and external surface of pressure tubes which could be discerned by the scratches due to frequent removal and insertion of fuel channel bundles [5]
- oxide zones and blistering due to zirconium hydrate forming on external surface of the pressure tube [6]

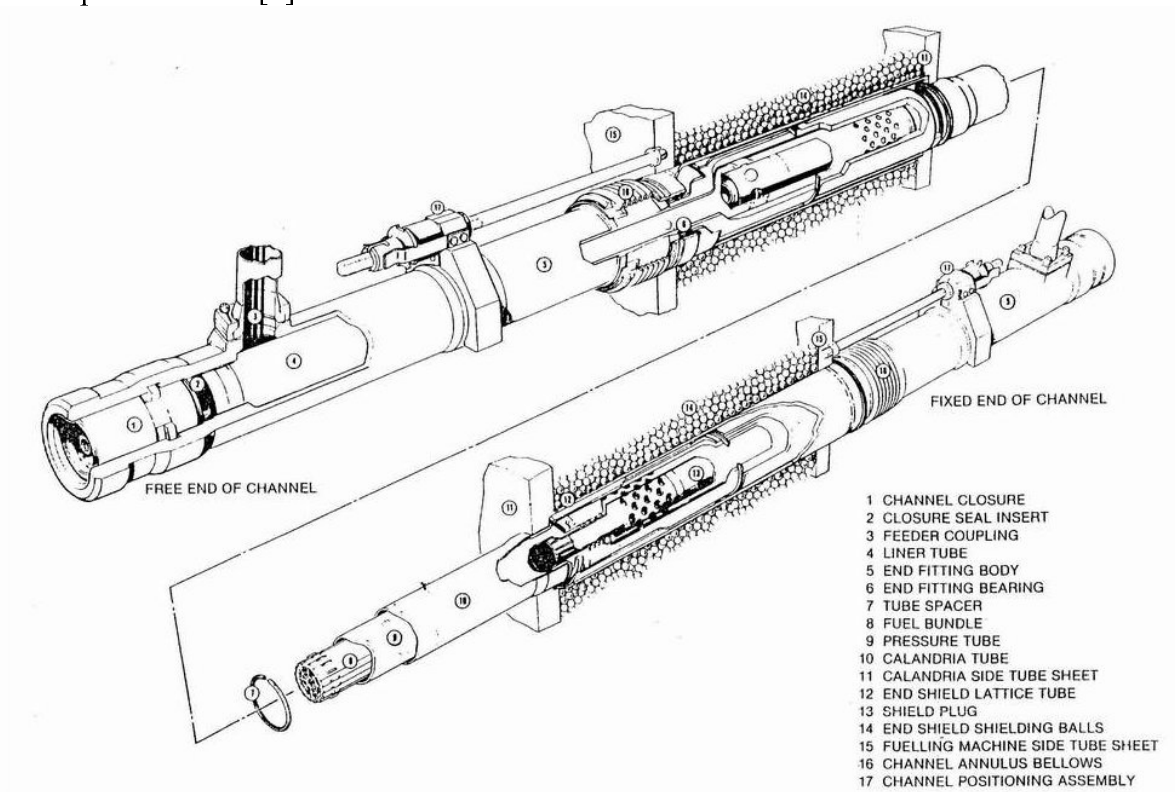


Fig. 1. The fuel channel assembly

For nondestructive evaluation of pressure tubes several equipments, transducers, inspection techniques and signal processing methods have been developed over the years and, the results obtained have been compared as a part of a coordinated research project under the auspices of International Atomic Energy Agency – Vienna [7].
This paper presents a novel type of eddy current transducer using rotating magnetic field for nondestructive examination of fuel channels.

THE CONTROL EQUIPMENT

The transducer is absolute send-receiver type, and a schematic of the transducer is presented in Figure 2. The transmitter is made from 3 rectangular coils, wound with $2\pi/3$ angle between them, star connected and supplied with a three-phase electric current. The vector addition of the magnetic fields created by the 3 coils results in a magnetic rotating field, with the frequency being equal to that of the three-phase current [8]. The receiver is made of an equally spaced array 24 identical coils, which are consecutively interrogated through an analogical multiplexer.
Three programmable function generator cards AWG 7223 PC-2 type supply the circuit with the three phase alternative current, as well as the reference for synchronous detection. The signals are amplified and applied to the transmitter creating a rotating magnetic field. The 24 receiver coils are consecutively interrogated, and connected to the input of an SFT 6000N eddy current board [9].

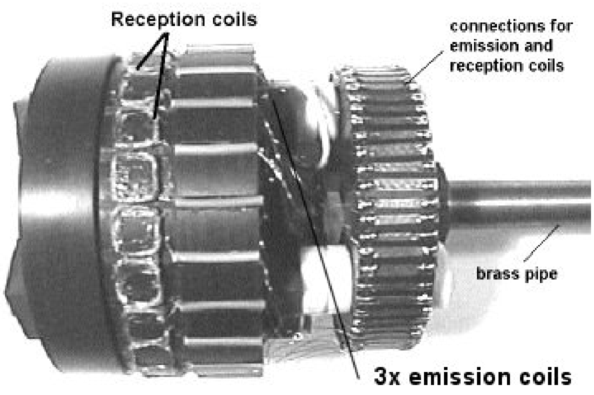


Fig. 2. The inner eddy current transducer with rotating magnetic field

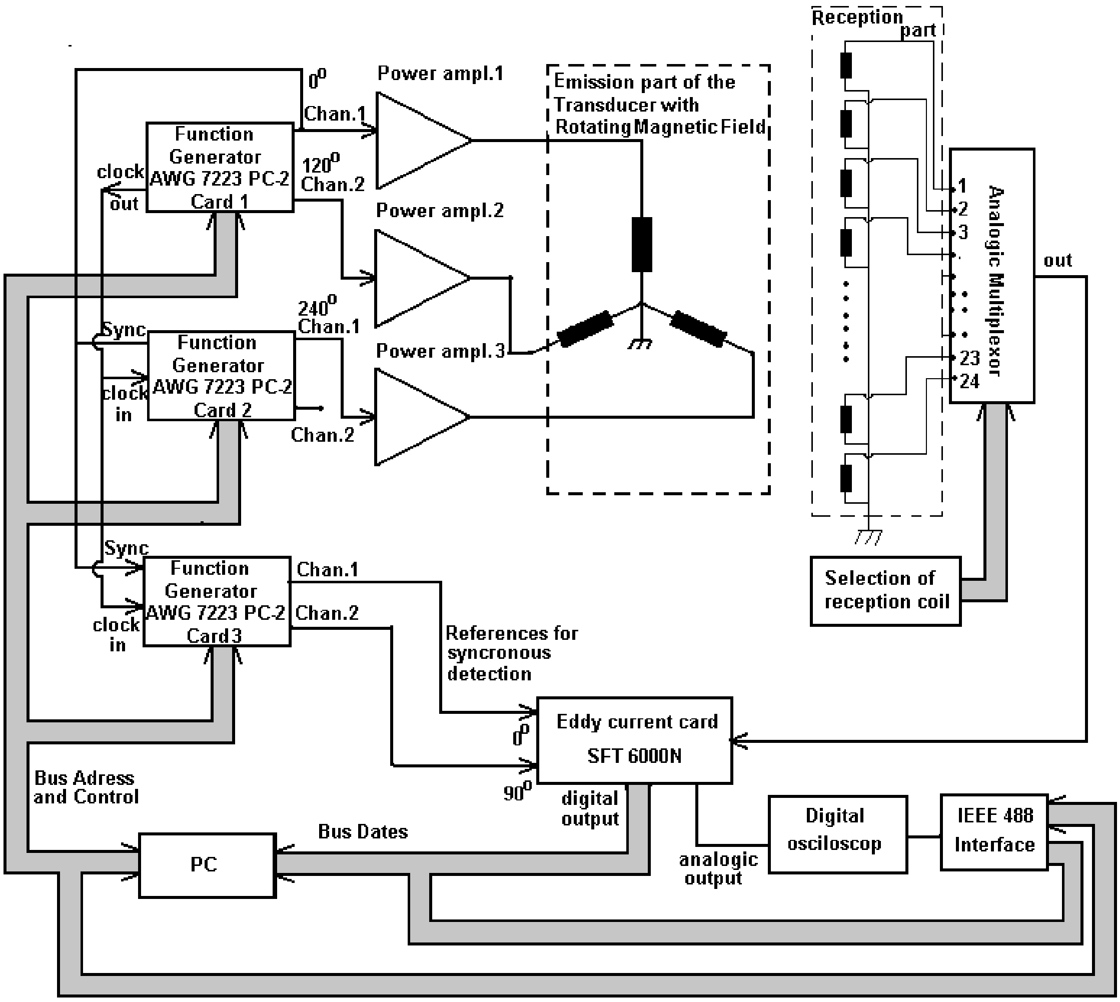


Fig.3. Experimental set-up

DETECTION OF DISCONTINUITIES

The RMF transducer was used to detect discontinuities in un-irradiated pressure tube samples with 103 mm internal diameter and 4.2 mm wall thickness. A set of 42 defects with different shapes and severities were machined in the tubes.

In Figure 4 we present the signal delivered by the control equipment for 3 types of discontinuities, placed approximately on the same generatrix (Figure 5 a, b, c).

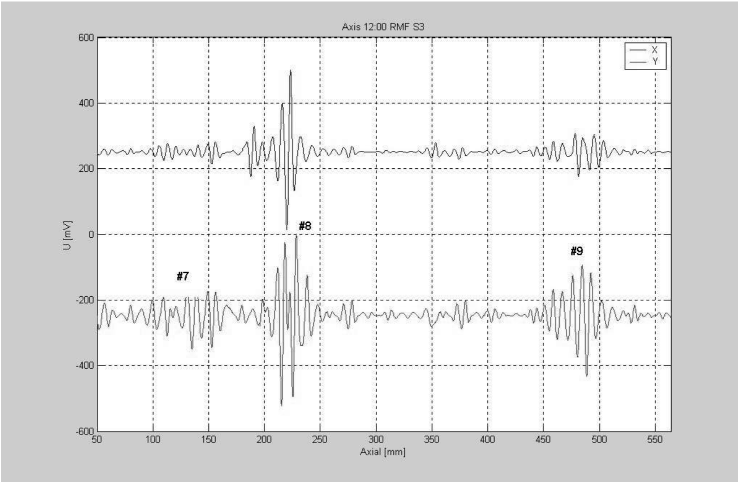
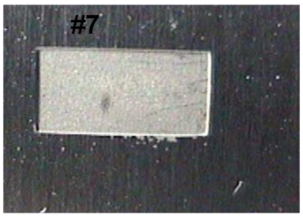


Fig.4. Experimental results

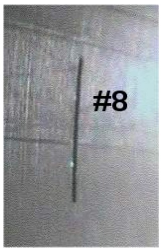
The control parameters were frequency 40KHz, current 0.1A, gain 56dB, phase 202^0, axial scanning step of 0.25mm. The transmitter coils have 70 turns each, with a winding area of 56x92 mm dimensions and 4 mm height. The 24 receiver coils have each 70 turns, 0.1mm diameter wire winding and area of 8x10 mm.

It can be seen from Figure 4 that the discontinuities from internal surface, as well as from external surface are clearly emphasized.

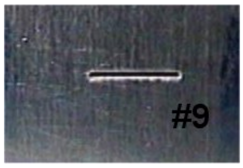
The signal to noise ratio for the discontinuity #7 (that delivers the minimum signal) is higher than 3.



OD rubbing mark (length 16mm, width 8mm, depth 0.2mm);



ID circumferential (width 0.2mm, length11mm, depth 0.2mm);

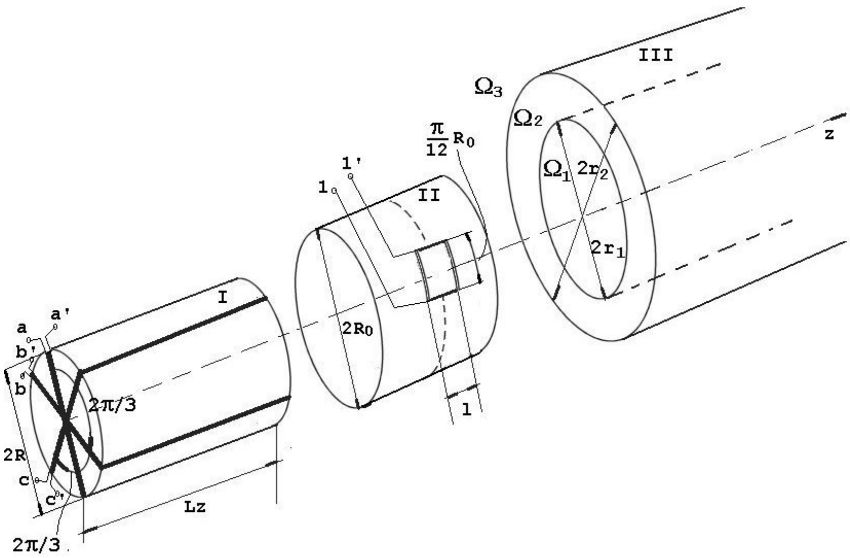


OD axial (length 6mm, width 0.4mm, depth 1mm)

Fig.5. The discontinuities

THE FORWARD PROBLEM

The transducer- tube assembly is presented in Figure 6 in cylindrical coordinates.



I – emission part (a-a', b-b', c-c' – emission coils connections)
II – reception part (1-1', .., 24-24' – reception coils connections)
III – the controlled tube - Ω_1 interior of tube , Ω_2 tube's wall, Ω_3 exterior of tube)

Fig.6. The transducer- tube assembly:

Using dyadic Green's function method, for the cylindrical layered media [10], the electric field in the tube's wall (Ω_2) can be written as

$$\overline{E}_2(\overline{r}) = j\omega\mu_0 \int_{Vsource} \overleftrightarrow{G}_{12}(\overline{r},\overline{r}')\overline{J}(\overline{r}')d\overline{r}' \tag{1}$$

where $\overline{J}$ is the current source as given in [11] and ω is the frequency.
The presence of a discontinuity in Ω_2 is equivalent to an auxiliary current source that creates the field

$$\overline{E}_f(\overline{r}) = \overline{E}_2(\overline{r}) + j\omega\mu_0 \int_{Vflaw} \overleftrightarrow{G}_{22}(\overline{r},\overline{r}')\left[\overline{E}_f(\overline{r}')\left(\sigma - \sigma_f(\overline{r}')\right)\right]d\overline{r}' \tag{2}$$

where σ_f is the electric conductivity of flaw.
The electric field generated by the discontinuity in Ω_1 (where transducer is placed) is

$$\overline{E}_1(\overline{r}) = j\omega\mu_0 \int_{Vflaw} \overleftrightarrow{G}_{21}(\overline{r},\overline{r}')\left[\overline{E}_f(\overline{r}')\left(\sigma - \sigma_f(\overline{r}')\right)\right]d\overline{r}' \tag{3}$$

The electromotive force, induced in one of receiver coils is

$$e = -\int_{\Gamma} \overline{E}_1 d\overline{\ell} \tag{4}$$

where Γ is the coil contour.
The dyadic Green's functions for layered media have the expression

$$\overleftrightarrow{G}_{lm}(\overline{r},\overline{r}') = \frac{5}{8\pi}\int_{-\infty}^{\infty} \frac{1}{k_m^{\ 2}\gamma_l^{\ 2}} \overline{D}_\mu \overline{F}_n(\rho,\rho')\overleftarrow{\overline{D}}{}_\varepsilon^{1t} e^{jk_z(z-z')}dk_z - \frac{\hat{\rho}\hat{\rho}}{k_m^{\ 2}}\delta(\overline{r}-\overline{r}') \tag{5}$$

where

$$\begin{aligned} k_m^{\ 2} &= \begin{cases} \omega^2\mu_0\varepsilon_0 & m \in \{1,3\} \\ \omega^2\mu_0\varepsilon_0 + j\omega\mu_0\sigma & m \in \{2\} \end{cases} \\ \gamma_l^2 &= k_l^{\ 2} - k_m^{\ 2}, \qquad l \in \{1,2,3\} \\ \overline{D}_\mu &= \left[\nabla\times\nabla\times\hat{z}, j\omega\mu_0\nabla\times\hat{z}\right] \\ \overleftarrow{\overline{D}}{}_\varepsilon^{'} &= \left[\nabla\times\nabla\times\hat{z}, j\omega\mu_0\nabla\times\hat{z}\right] \end{aligned} \tag{6}$$

The operator $\overleftarrow{\overline{D}}{}_\varepsilon^{'}$ operates on the primed coordinated to its left.
The function $\overline{F}_n(\rho,\rho')$ has different expressions depending on the position of source and the observation points [10]. The last term on the right hand side of eq. (5) represents the singularity of Green's function $\overleftrightarrow{G}_{22}$ when the observation point coincides with the current point on the source.
The eq. (2) was discretized using the method of the moments, the point-matching variant. The numerical code was developed in Matlab 6.5 using 64x128 spatial harmonics.

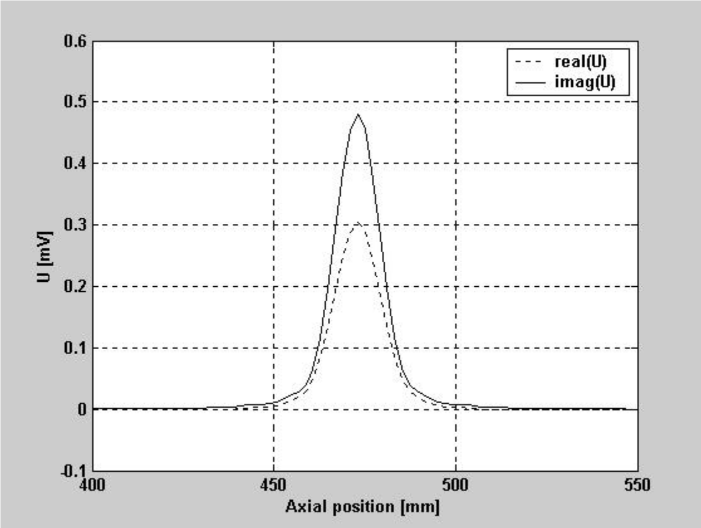


Fig.7. Solution of forward problem

In figure 7 we present the solution of forward problem for the discontinuity #9 with the dimensions described in Figure 5. The defect region was discretized using 6x1x10cells. The shape and the position of the simulated signals reproduce correctly the experimental measurements shown in Figure 4, for the discontinuity #9.

CONCLUSIONS

For nondestructive examination of pressure tubes from PHWR, the eddy current transducer with rotating magnetic field is used to detect discontinuities placed on internal and external surface of the tube. The forward problem for the transducer with rotating magnetic field was solved, a numerical code in Matlab 6.5 being developed. The simulation's results are in very good concordance with experimental measurements.

ACKNOWLEDGMENTS

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