## *Queen's University – Lynann Clapham CRD*

NSERC/UNENE Collaborative Research and Development Grant on Measurement of near-surface residual stress in CANDU feeder pipes using magnetic non-destructive evaluation techniques

### 1.1 Objective and Introduction

<u>The objective of the proposed work is to develop a magnetic non-destructive evaluation (NDE) probe for measuring residual stresses in CANDU feeder pipes.</u> These feeder pipes, which are typically mild steel with a 60mm diameter OD with a 7mm wall thickness, transport heavy water coolant into and out of fuel channels in CANDU nuclear reactors. Residual stresses (strain) in these feeders has become a concern after cracks were discovered in some bend regions. A tool for non-destructively evaluating residual stresses in these feeders is needed, and is the focus of this project. The work is co-funded by NSERC and UNENE, the University Network of Excellence in Nuclear Engineering, with in-kind support from AECL.

Common NDE methods based on ultrasonics or eddy currents are relatively insensitive to strain. Magnetic NDE techniques are strain sensitive, but a number of practical difficulties limit their widespread use for this purpose. The two magnetic NDE techniques that are being investigated in this project are based on Magnetic Barkhausen Noise (MBN) and Magnetic Flux Leakage (MFL) principles. Application of either MFL or MBN to feeder pipe strain measurement requires consideration of the following:

1. Residual stresses are notoriously difficult to non-destructively measure and quantify, particularly in in-service engineering components.
2. Consistent strain detection using either MBN or MFL is highly dependent on experimental conditions such as probe lift-off and sample surface preparation.
3. Feeder pipes have over 18 different bend configurations, so the probe will have to be able to adapt to changing surface curvatures.
4. Feeder pipes are very closely packed at the CANDU reactor face, so access to the entire pipe surface will be limited and clearance will be a significant problem.
5. The working environment of the probe at the CANDU reactor face is radioactive, so human manipulation of the measurement probe is necessarily limited.

The work for this project began in July, 2005. The work plan for the first year was to investigate both MFL and MBN techniques to determine which would prove to be the best candidate technique for further development. This work was mainly the task of Steven White, a PhD student on this project, with additional assistance provided by a summer student (Ben Lucht) and a 4th year Engineering Physics undergraduate thesis student (Paul Webster). After a year of investigating MBN and MFL, it was clear that BOTH have strong potential for this application. As a result, from year 2 onwards the project was split into two complementary projects:

1) <u>To develop an MBN probe for residual strain measurement in CANDU feeder tubes.</u> This aspect of the project formed the basis for the PhD thesis work of Steven White. Steven completed this work in the summer of 2009 and is now in the process of writing 3 papers about his thesis work (earlier he published one paper and has presented in one conference). In addition to Steven, undergraduate research assistants (Kris Marble, Tom Mak and Davin Young) were involved in this aspect of the project as part of their summer projects.
2) <u>To develop an MFL probe for residual strain measurement in CANDU feeder tubes</u>
   During the summer of 2006 an undergraduate summer RA (Tom Mak) laid much of the groundwork for the experimental aspects of this project. An MSc student (Ryan Yee) was to begin working on the project Sept 2006, however in late August this student informed me that he had a job and wasn't going to pursue the project. As a result work on this aspect of the project was delayed for one year. However Tom Mak returned in September 2007 as an MSc student to work on this project. He has now completed the bulk of the experimental work on his thesis project and is writing his thesis. He is expected to be finished by December 2009.

By the end of the project had made considerable progress towards developing a working probe for the residual stress evaluation in CANDU feeders. As important, however, is the fact that we also considerably advanced the scientific knowledge and technological applications of both techniques. A summary of both aspects of the project (1 and 2 above) are summarized below.

### 1.2 Development of an MBN technique for the measurement of stress in CANDU feeders

MBN has been recognized for many years as having the potential for non-destructive stress measurement, but two main practical limitations have prevented its development beyond the lab:

1. The technique is highly sensitive to the lift-off of the probe from the surface, with slight variations causing significant signal variations. <u>This project has overcome this problem by introducing a feedback mechanism for controlling the flux into the sample, regardless of the liftoff.</u> This is discussed in section 1.2.1 below.
2. While our group has pioneered an angular MBN strain scanning method, our traditional technique involves physically rotating the MBN probe.

While this is adequate for flat plate samples, it is not suitable for curved feeder pipe surfaces. In this project, a new 4-pole (tetrapole) probe which does not need to be mechanically rotated, rather a variation in the flux introduced through the 4 poles effectively "rotates" the field. This is introduced in section 1.2.2 below. Furthermore, considerable modelling work has been conducted in order to optimise the tetrapole magnet design (section 1.2.3) and also the pickup coil design (section 1.2.4), and signal processing (section 1.2.5).

1.2.1 Addressing lift-off issues: As mentioned above, lift-off/surface contact problems represent a significant obstacle to the application of this technique. Magnetic modelling was conducted at Queen's and AECL to study exciter coil placement and the effect of feedback on the excitation field. This suggested that a pole-piece mounted feedback coil would help to decrease lift-off sensitivity. Using the modelling result as a guide, PhD student Steve White designed and built a number of probes having different feedback coil parameters, in addition to modifying and re-designing the instrumentation needed to drive and interpret signals from the probes. Figure 1 shows the MBN probe coil geometry including the flux sensing (feedback) coil.

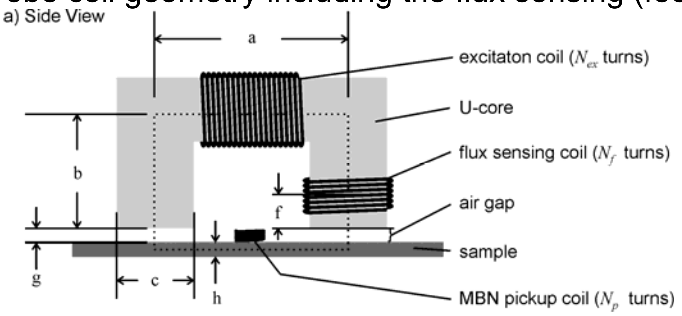


**Figure 1: Decoupled MBN probe with feedback (flux sensing) coil constructed as part of the project.**

Steve also investigated different possible methods for driving and feedback, evaluating the relative merits of controlling the probe using magnetic field (H) control, and magnetic flux (B) control. He has shown that feedback flux control is a superior method for attaining MBN signal consistency despite liftoff. Figure 2 illustrates this – Fig 2(a) shows that the MBN result with field control varies considerably with liftoff, while Figure 2(b) indicates that the result for all liftoff conditions is similar if one uses flux feedback control.

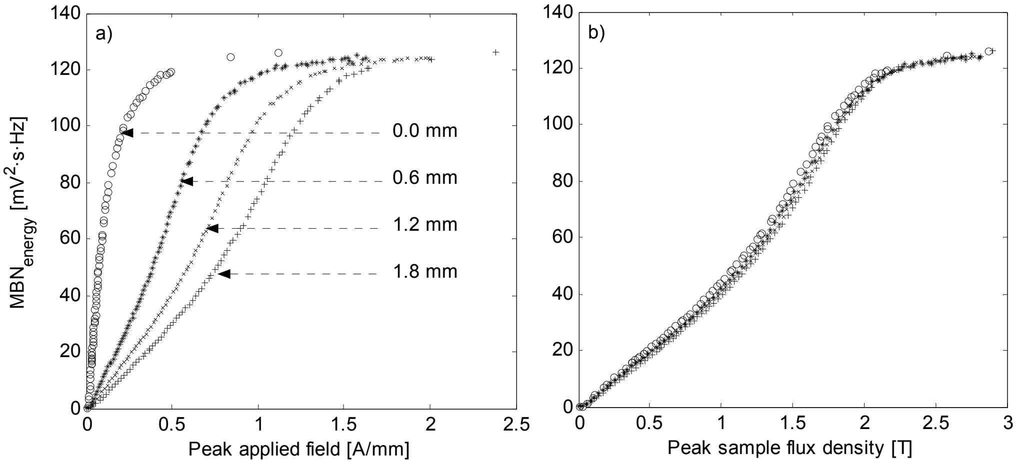
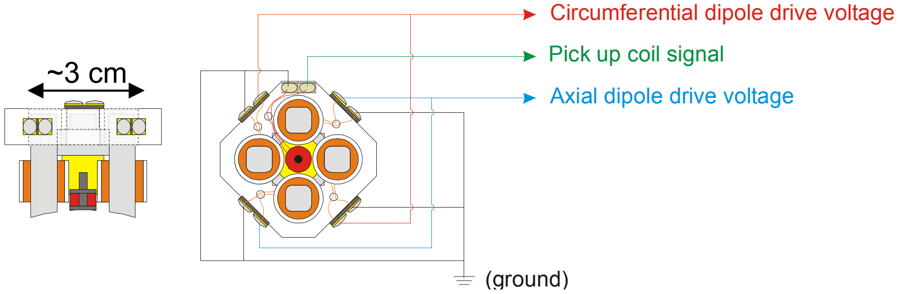


**Figure 2: MBN$_{energy}$ lift-off response (for liftoff values of 0, 0.6, 1.2 and 1.8mm) as a function of a) applied field and b) sample flux density for the Si-Fe steel sample**

<u>1.2.2 The new tetrapole design</u> Since physical rotation of the coil is problematic on a non-planar surface, Steve developed a probe that will perform an angular MBN measurement without the need for physical rotation – rather the field rotation will be done electronically. His design involves two perpendicular dipole probes – to create a "tetrapole" probe, as shown in Figure 3. Varying the amplitude/phase of the exciter signal in each probe is expected to produce an angular vector superposition of the magnetic field in the sample, thus accomplishing a rotation of the MBN exciter field without the physical probe movement of the probe, as illustrated in Figure 4.



**<u>Figure 3:</u> "Tetrapole" probe (left) and also schematic in side view (middle) and bottom-up view (right).**

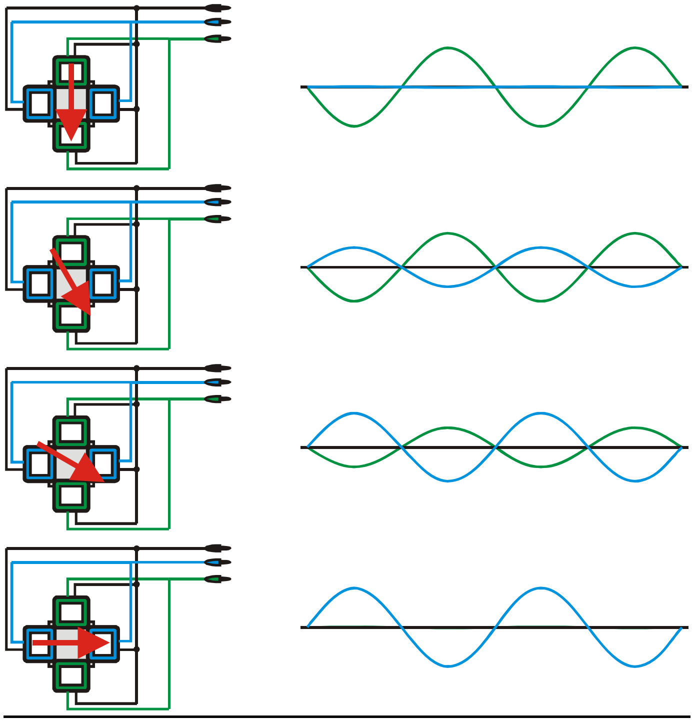


**Figure 4:** "Tetrapole" probe operation – rotating the field at the centre of the probe by varying the field in the set of blue dipoles and the set of green dipoles. The red arrow on the tetrapole schematic indicates the sum field direction.

### 1.2.3 Tetrapole modelling

Once the basic tetrapole magnet was design was constructed and working, a considerable amount of modelling work was conducted to examine how best to modify and optimise the design. Figure 5 shows models of two different tetrapole designs considered in this phase of the project. An example modelling result is seen in Figure 6, which shows the effect of tetrapole coil driving frequency on the flux pattern in the sample flux distribution.

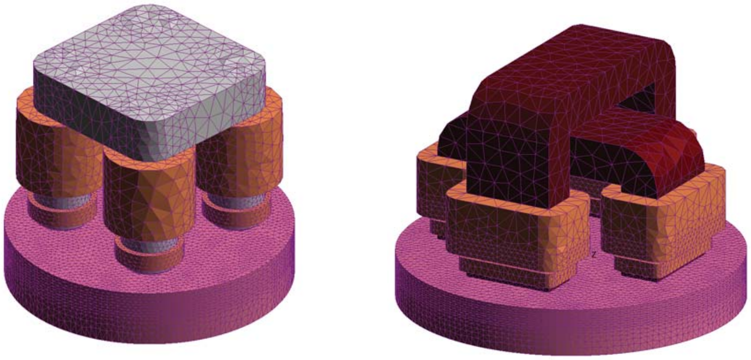


**Figure 5:** Two different tetrapole designs evaluated during the modelling phase

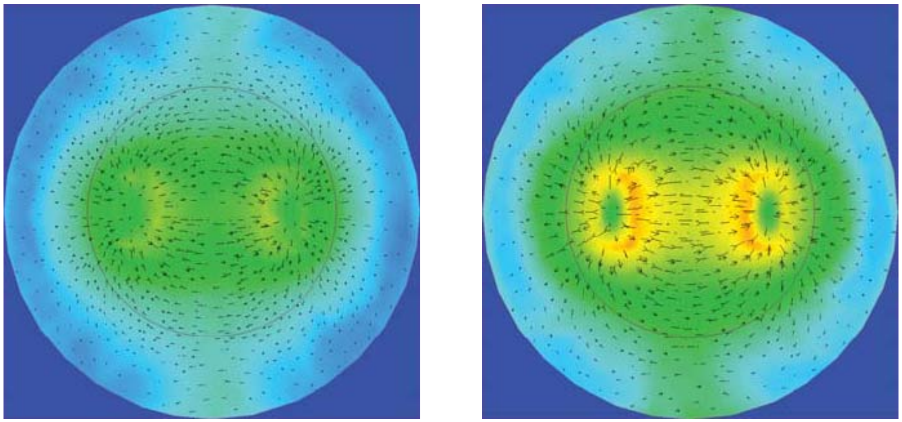
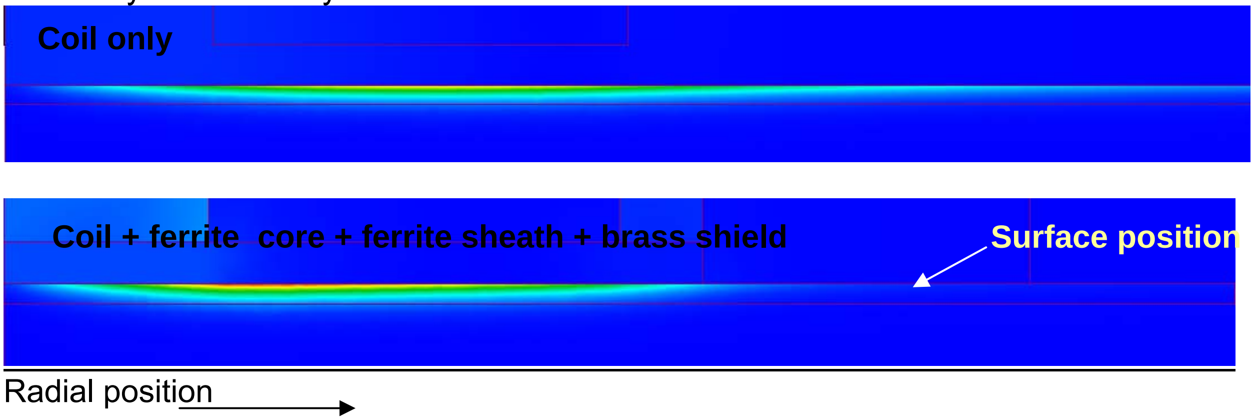


**Figure 6:** **modelling results for the tetrapole design at the left of Figure 5 – for two different driving frequencies. The diagram on the left is for a frequency of 10Hz, the**

1.2.4 Pickup coil modelling

The pickup coil sits at the centre of the tetrapole magnet arrangement and detects the MBN signals. In addition to tetrapole exciter coil modelling, a considerable amount of modelling was done to determine the optimum configuration and composition for the pickup coil design. A number of different configurations were considered – a bare coil, a coil with a ferrite core, a coil with an external brass shield, and a coil with an external ferrite sheath. All combinations of the above were also considered. Figure 7 shows the cross section through the centre of the sample region – indicating the area sensitivity of the composite pickup coil.

Figure 7: showing that composite pickup coil has greater, more localized sensitivity than coil only



1.2.5 Signal processing

Work on signal analysis and processing also formed a significant part of the final stages of the thesis work. Figure 8 shows results of signal processing before and after filtering.

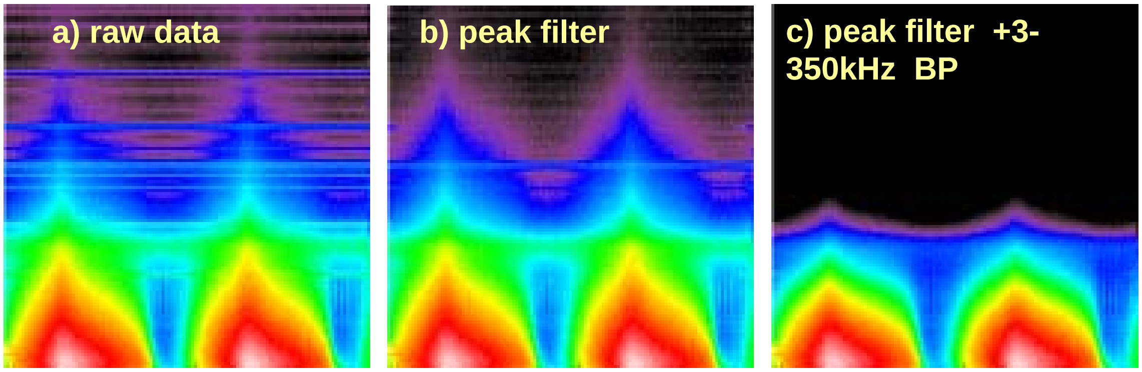


Figure 8: shows the averaged Power Spectral density of Barkhausen noise as a function of the excitation coil phase for 128 BN cycles at 58Hz. The streaks in the raw data are resonances in the background noise spectrum and are not associated with BN. b) A soft digital peak filter decreases the power of these artefacts. c) A 3rd order Bessel band pass filter is applied between 3 and 350 kHz. This creates a very clean BN spectrum

## 1.3 Progress towards objectives: MFL technique

A magnetic flux control system was designed that implements integral (Hall sensor) and proportional (coil) feedback. This system, shown in figure 10, allows specification of the magnetic flux density through the feedback coil and Hall sensor, which is then converted in LabView to a reference voltage $V_{ref}$. The output voltages of the feedback coil ($V_{fc}$) and Hall sensor ($V_{h+}$ and $V_{h-}$) are compared to the reference voltage. The amplifier adjusts its output such that $V_{ref} = V_{fc} + V_{h+} - V_{h}$ when $R_{vh} = R_g = R_{fc}$.

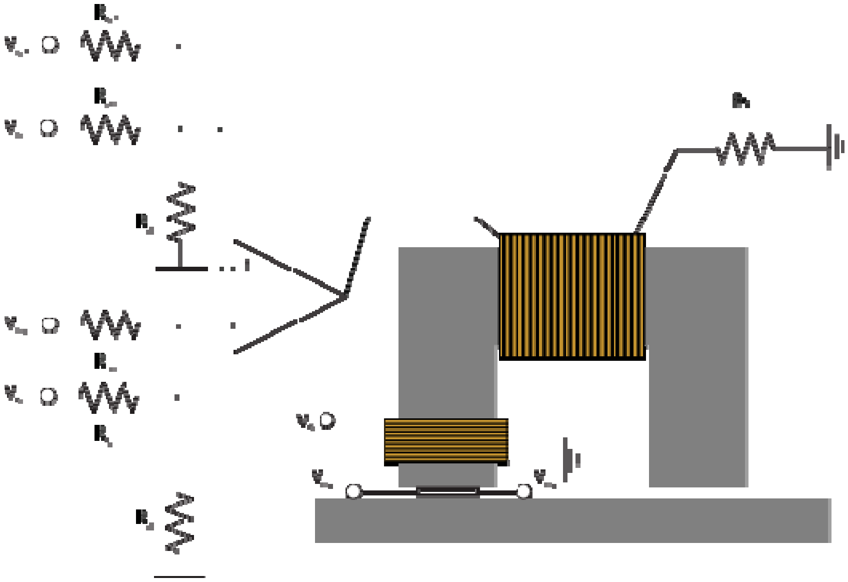
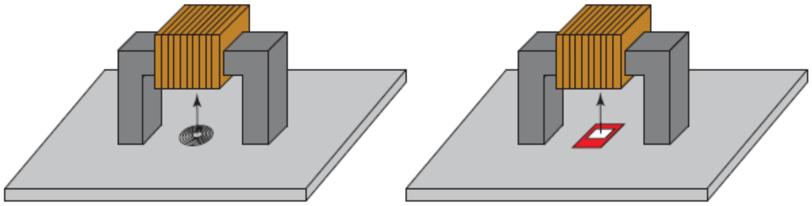


**Figure 10:** A simplified schematic of the proportional-integral flux control system. Excitation and feedback coils are wound onto a U-core magnetic. Between the

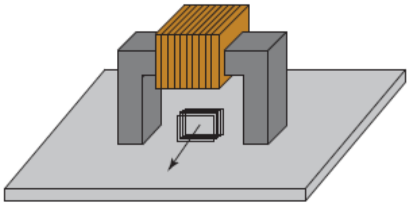
magnet and sample is a Hall sensor, which provides integral feedback to the control system.

This control system was tested on mild steel plate samples in a single axis stress rig (SASR) with three flux leakage sensors (shown in figure 11): a coil with its axis parallel to the sample surface normal, a Hall sensor oriented parallel to the surface normal, and a sensing coil set perpendicular to the applied magnetic field and the surface normal (referred to as the anisotropy sensor). The first two measurements were preformed twice: once with the magnetic field parallel to stress, then with the field perpendicular to stress. Neither of these measurements indicated significant MFL stress sensitivity.



AC MFL:
Coil with its axis parallel to the surface normal

DC MFL:
Hall sensor oriented parallel to the surface normal



Anisotropy:
Coil oriented perpendicular to both the applied magnetic field and the surface normal

Figure 11: three different MFL probe designs tested

The anisotropy sensor was rotated about 360°; measurement data was acquired in increments of 15°. Anisotropy signal amplitude varied sinusoidally with a period of 180°, shown in figure 2. Increased stress levels produced a noticeable effect on the anisotropy signal. To quantify this effect, anisotropy signals were calibrated to a background measurement at zero stress. These calibrated signals were fit in MATLAB as 180° periodic sine waves, and the amplitudes were extracted.

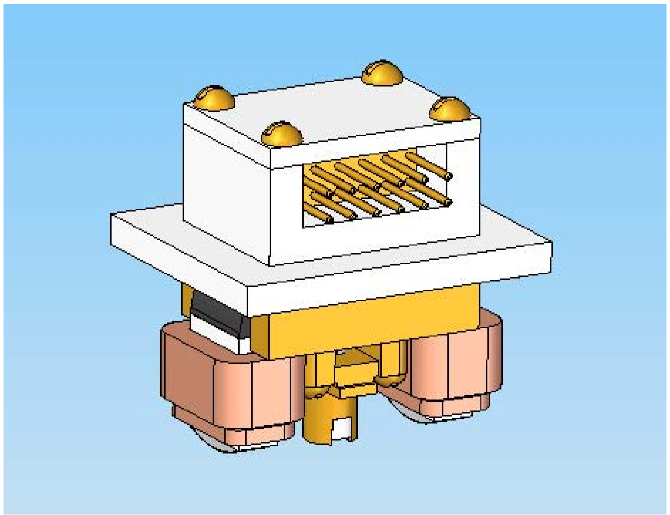


**Figure 12:** A modified anisotropy sensor designed to mount on curved pipe surfaces. The mounting bracket is omitted from this figure for clarity. The sensing coil is located between the poles of the U-core and is spring mounted.

Finally, a new sensor was built to test the anisotropy system for use on CANDU feeder pipes. This is shown in Figure 12. The system was miniaturized and modified to function on curved surfaces, and is still undergoing testing.

Table Submission
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| Name | Type of Trainee |
|---|---|
| Lucht, Benjamin | Undergraduate |
| Mak, Thomas | M.Sc. |
| Webster, Paul | Undergraduate |
| White, Steven | Ph.D. |
| Young, Davin | Undergraduate |