ABSTRACT

Eddy Current Testing (ECT) is a powerful mean of detection of defects located in the conductive components. This mean of detection has already proven efficiency in many applications, in domains as various as aeronautics, automotive or nuclear energy. Concerning this industry, the integrity of components exposed to stress or and corrosion is a critical issue. In consequence, EC probes have to be reliable and designed to bring the most adapted solution.

Health monitoring of Steam Generator (SG) tubes using ECT constitutes a real challenge considering the great number of degradations observed in industrial installations. Typical flaws affecting these tubes are longitudinal or transverse cracks due to the sensitivity of the Nickel-based alloy 600 to stress corrosion cracking. The inspection of SG tube is all but easy because of the geometry of the tube itself. Indeed, elliptic deformations may appear and its diameter shows a slight variation at the Top of the Tube Sheet (TTS). The benefit of using flexible EC probes for tubing inspection is discussed in this paper.

In the framework of a study carried out by IRSN and CEA LIST, simulations have been performed using tools recently appended to the CIVA Non Destructive Techniques (NDT) platform developed at CEA LIST. Simulation tools provide important information about flaws detection and NDT devices improvement. This study led to the design of an original sensor, based on micro-coils. Simulations of classical cases reinforce the interest of the optimised design, especially for the detection of transverse defects.

With regards to the good performances shown during the simulation study, a prototype probe has been developed. To bring flexibility to the probe, the micro-coils have been etched on a flexible film, whose shape fits with the geometry of the tube. Experimental tests show the good performances of the prototype probe, even in the detection of defects located in the section where the diameter of the tube varies.

Another technology is investigated at CEA LIST to design flexible EC probes. Its principle is to embed the sensor into a material which has the property to be elastic, as silicone for example. A flexible probe based on a Giant Magneto-Resistance sensor has been developed using this technique. Experimental testing reveals good performances in the detection of deep defects at low frequency.

INTRODUCTION

The inspection of complex nuclear components such as steam generator tubing, nozzles and bottom head penetration with efficient techniques is an important issue for safety. The classical eddy current probes are based on coils made of wound copper wire and are consequently rigid. Therefore, they are mostly efficient for the detection of flaws located in planar components and lift-off variations usually have deleterious effects on the probe sensitivity and on the signal to noise ratio. Furthermore, the sensitivity of a coil decreases linearly with respect to the frequency and the sensitivity of conventional probes at low frequency might be too low to detect deeply embedded flaws. To solve these problems, the CEA LIST has developed advanced eddy current probes for Non Destructive Testing (NDT): flexible array probes based on micro-coils for the detection of flaws in complex shaped components [1] and high sensitive probes based on Giant Magneto-Resistance for the detection of deeply embedded flaws [2]. The designs of the probes have been optimized thanks to the CIVA software [3] which is a powerful multi-techniques (ultrasonic, radiographic, electromagnetic) simulation platform dedicated to NDT.
In this paper, the performances of two EC probes and their potential benefits for nuclear applications is presented. The first part describes the development of a flexible EC probe dedicated to the inspection of SG tubes. Simulations and experimental results are given and compared. The second part is about the benefits of using Giant Magneto-Resistance sensor in NDT applications [4]. A flexible EC probe based on GMR is presented and experimental results are shown.

**INSPECTION OF STEAM GENERATOR TUBES**

**Context**

The inspection of steam generator tubes turns out to be an arduous operation from different reasons that can be separated into two origins. On one hand, difficulties come from their own geometry: their length and number impose fastness and accuracy, the use of support plates requires inside inspection and variation of tube’s diameter in Top of the Tube Sheet (TTS) area needs fitting and flexibility. On the other hand, some problems are due to the typical defects that may appear. Indeed, longitudinal, transverse or combinations of both have to be detected and characterised. Eddy Current technique has assets to bring solutions to these applications.

**Development of a flexible EC probe**

Considering the constraints listed above, EC probe have to match with some specifications. First one is flexibility to allow the whole inspection of the tube, even in TTS area. Moreover, flexibility reduces noise coming from lift-off variation and is an asset to get good Signal to Noise Ratio (SNR). Second requirement is the good sensitivity of the sensors used to make the probe reliable and efficient. Last but not least could be called the smartness of the probe. To be able to identify complex defects and make characterization, the design of its sensitive area has to be studied and optimized cautiously. In particular, transverse defects have to be looked into with attention since they are a critical point for breakdown of the tube.

Research has been completed at CEA LIST with the support of the Institut de Radioprotection et de Sûreté Nucléaire (IRSN). The aim was the optimization of a sensitive pattern, specially designed for SG tubes inspection and its packaging into a specific EC probe. Simulations using CIVA platform have therefore been done in order to define the characteristics of the emitter and the receiver regarding the geometry of the parts and the defects to be detected. The study leads to the design of a separated function sensor. Emitter is composed with a current coil that allows a good orientation of the EC into the component, useful for the identification of longitudinal or transverse defect. Receiver consists in high sensitive micro-coils.

The performances of this new design have been evaluated by simulation, regarding typical cases that may occur in nuclear plant.

**Simulation evaluation**

First configuration addresses a through wall (100% thickness of the tube) longitudinal defect, which size is 7mm x 0.15mm. C-SCAN at 240 kHz of the internal inspection of the tube is given in Figure 1. The defect is clearly detected and the accuracy of the signature makes sizing possible. This signal gives an amplitude reference for the other studied defects.
Second case is a 40% external transverse defect, which size is 0.15mm x 6mm x 0.51mm. C-SCAN at 240kHz is shown on Figure 2. The probe allows an easy and good identification of this defect with amplitude similar to the one of the longitudinal flaw.

Third, fourth and fifth configurations are combinations of the two previous defects. The first one is a “T-shaped”, the second one is an “L-shaped” while the third one is a “+ shaped”.

C-SCAN at 240 kHz of the “T-shaped” defect is presented on Figure 3. The new design allow to distinguish the two defects. Thanks to projections (respectively 20° and 110°), both defects are easily identified and the transverse flaw can be discriminated.
C-SCAN at 240 kHz of the “L-shaped” defect is presented on Figure 4. The complex defect is detected and its two components are easily identifiable.

C-SCAN at 240 kHz of the “+shaped” defect is shown on Figure 5. The new probe detects the +shaped defect. Real and imaginary parts of the signal allow to discriminating both components of the complex defect.
As simulations had validated the performances of the new pattern regarding the detection of complex defects located into tubes, an EC probe based on this design has been developed. To make the probe flexible, both emitter and receiver had to be etched on a specific flexible film instead of classical PCB. This constraint leads to packaging difficulties but had been solved using Kapton. To enhance the SNR, electronics have been put as close as possible to the sensitive area. The probe is driven by a helicoidally rotation to make the inspection of the whole tube possible. A photo of the EC probe is given on Figure 6.

**Experimental results**

To validate the flexibility concept, experimental testing has been performed in the TTS area where the diameter of the pipe varies. Two identical defects have been machined, one in the area where the diameter is constant and one in the part where it increases. Both are 6mm long, perpendicular to the pipe and 40% external. As shown on Figure 7, the CSCAN at 240 kHz reveals that both defects are as well detected. The flexibility of the probe proves efficiency.
Figure 7 - a) configuration studied - b) Experimental CSCANs at 240 kHz for a 40\% ext transverse defect located into two areas of the pipe: where the diameter is constant – where it goes from 22.2mm to 22.6mm (TTS area)

Three defects have been machined into the mock-up where the diameter of the pipe is constant. They are similar to the defects studied during simulation evaluation. The first one is a 10mm, 100\% longitudinal, the second one is a 8mm, 40\% external transverse notch and the last one is “L-shaped” arrangement of both. As expected regarding the simulation results, the three defects are detected with a good SNR (20dB) as shown on Figure 8.

Figure 8 - a) mock-up with 3 defects: 100\% long (10mm), 40\% ext Trans (8mm), both « L » shaped – b) experimental results @ 240kHz

Experimental tests have also been performed in TTS area. The machined defect consist in a “T-shaped” arrangement between one 10mm 100\% longitudinal defect and a 8mm 40\% ext transverse defect. Experimental result at 240 kHz is given on Figure 9 and compared to simulate one. It reveals a good agreement between simulation and measurements and the new probe is able to make a good characterization on the complex defect.
Figure 9 - a) mock-up with an L-shaped defect: 100% long (10mm), 40% ext Trans (8mm) in the TTS area - b) experimental results @ 240kHz – c) simulation results @ 240kHz (CIVA)

The new probe has shown great performances in the detection of complex shaped defects. Experimental results are close to the computed ones and confirm the efficiency of the probe in the free span region of the tube as well as in TTS areas.

DEVELOPMENT OF AN EC PROBE BASED ON A GMR SENSOR

The challenge of the second development is the detection of deeply embedded flaws. For skin depth effect reason, low frequency is required to detect defects when their ligament increases. For a given diameter, coil sensitivity decreases when frequency decreases. Other technology has to be investigated to bring solutions. That is why a EC probe using a Giant Magneto-Resistance (GMR) as sensor has been developed at CEA LIST with the support of IRSN. Indeed, GMR sensors reveal several advantages for NDT [4]:

- despite their small size (~100µm) they remain high sensitive in a large frequency range
- low noise provides the capability of detecting deeply embedded flaws,
- low cost makes them attractive for developing commercial probes,
- the collective manufacturing process facilitates the making of large array probes.

EC probe based on GMR

A photo of the developed probe is given on Figure 10. A GMR sensor is used as receiver and two coils are available for induction. As their distance to the receiver is not the same (respectively 15mm and 20mm) the one to be used is chosen depending on the depth of the part to be inspected. To make the probe flexible, the elements have been embedded into silicone. Therefore, noise due to lift-off variation is reduced and complex parts (as welding) can be inspected.

Figure 10 - EC probe based on a GMR sensor for deep defects detection
Experimental results

To evaluate the performances of the EC probe, we used a stainless steel cylinder mock-up in which seven longitudinal notches have been made. The thickness of the cylinder is 12mm and the lengths and depth of the defects are indicated into the table of Figure 11. The inspection is performed from the external side thanks to a mechanical rotating support. A photo of the experimental configuration is given on Figure 11.

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Figure 11 - experimental test of the EC probe using a stainless steel cylinder- a) characteristics of the defects – b) photo of the experimental configuration

The winding coil used is located at 20mm from the GMR sensor. Two defects (10mm and 20mm) located at different depths (2mm, 4mm, 6mm and 8mm) have been studied at different frequencies (1kHz, 2kHz, 5kHz and 10 kHz). Corresponding skin depth is also indicated. The real part of the experimental results is given on Figure 12. For every depth, both defects are detected with a good SNR.

- Defect: L = 20mm, depth: 2 to 8 mm

- Defect: L = 10mm, depth: 2 to 6 mm

Figure 12 - EC probe base on GMR sensor. Experimental results for two defects (10mm and 20mm) located at different depths (2mm to 8mm) at different frequencies (1kHz to 10kHz)
CONCLUSION

A new EC probe dedicated to the inspection of SG tubes has been developed. The optimize design with CITVA software has proven good performances when simulated. Longitudinal, transverse and complex defects can be detected and identified. Thanks to a special integration on a flexible film, the developed EC probe is able to inspect tubes even if TTS areas. Experimental results are in good agreement with the simulations. Transverse defect can be discriminated from a longitudinal one, in classical cases (T, L and + shapes).

The benefits of Giant Magneto-Resistance sensors have been taken into account to develop an original EC probe dedicated to the detection of deep defects. The probe has show good results when used for the detection of notches located into a cylindrical stainless steel mock-up at different depths.

REFERENCES

3) http://www-civa.cea.fr