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Novel eddy current probes for pipes: Application in austenitic round-in-square profiles of ITER

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ABSTRACT

Novel eddy current probes were developed to detect sub-millimetre defects with any orientation on the inner surface of pipes. Five different probes were designed, produced and experimentally validated. These probes include arrays of planar trapezoidal coils in a flexible substrate used alone or together with different winded drive coils. Numerical simulations with Finite Element Method were used to predict the probe response to defects with any orientation. Experimental results in austenitic steel jackets used in ITER revealed that the new probes have an improved reliability compared to conventional toroidal bobbin probes, allowing a higher sensitivity to circumferential defects.

1. Introduction

Eddy Currents (EC) is one of the main non-destructive testing technique used to inspect metallic pipes and tubes [1]. The inspection of the outer pipe surface is performed during production with encircling EC probes, while inner pipe inspection is mostly performed after installation and in service, in industrial environments, for instance in steam generator pipes for nuclear power plants or boilers [2–4]. Despite being a very common technique, some difficulties remain, especially in the inspection of circumferential micro defects on the inner surface of low magnetic permeability materials ($\mu_r \approx 1$).

Conventional bobbin probes for inner pipe inspections are typically composed of circumferential windings inducing circumferential eddy currents. Defects with transversal orientation towards the EC direction produce output signals with greater amplitude, while defects with parallel orientation with the EC direction produce smaller output signals. In conventional coaxial windings probes, circumferential defects are parallel to the EC, thus, its poor proficiency to detect circumferential oriented defects [5].

In order to avoid the limitations of the conventional probes, different approaches have been essayed, such as the inclination of the bobbin windings allowing, for instance, different orientation between the pickup and the excitation coils which can be parallel, symmetric or twisted [6]. With this approach, EC are no longer parallel to the circumferential direction. These probes proved to have more sensitivity when compared to the conventional ones, however, there were circumferential positions, in which, the defects remain parallel to the coils, and thus, being overlooked without mechanical rotation of the probe.

Another approach for pipe inspection consists of a rotating field eddy current probe with bobbin pickup coil that generates a rotating magnetic field, avoiding mechanical rotation of the probe [7]. The authors used three identical coils located on axes of 120° apart and a balanced three-phase source. The vector sum of the fields generates a field that rotates circumferentially around the pipe. The probe was validated using artificial defects characterized by through wall square holes of $3.5\times4\ mm^2$ and $4\times4\ mm^2$ in Inconel® 600 pipes, with a conductivity of 9.69×10^5 S/m. The probe is sensitive to defects of all orientations in the tube wall and both depth and location to be estimated from a single line scan data. Later, this research group developed a new probe using a GMR as a sensor [8] with promising results. The prototype probe is sensitive to both axial and circumferential notches and the C-scan image clearly shows the defect location and orientation.

Probes composed of planar spiral coils arrays in flexible substrates, have shown to have superior reliability for micro defect detection,

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Table 1
Probe characteristics. (*l:* longitudinal; θ: circumferential).

Probe designation	Mode	Excitation direction	Signal type	Target defects
#1	Absolute	*l* and θ	Absolute	All
#2	Reflection	θ	Differential	Axial
#3	with	*l*	Absolute	Circumferential
#4	absolute	*l* and θ	Differential	All
#5	signal	*l* and θ	Differential	All

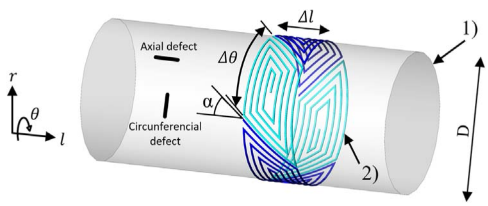

Fig. 1. Schematic representation of Probe #1 with absolute planar trapezoidal spiral coils. Legend: 1) Cylindrical chassis; 2) Trapezoidal spiral coils.

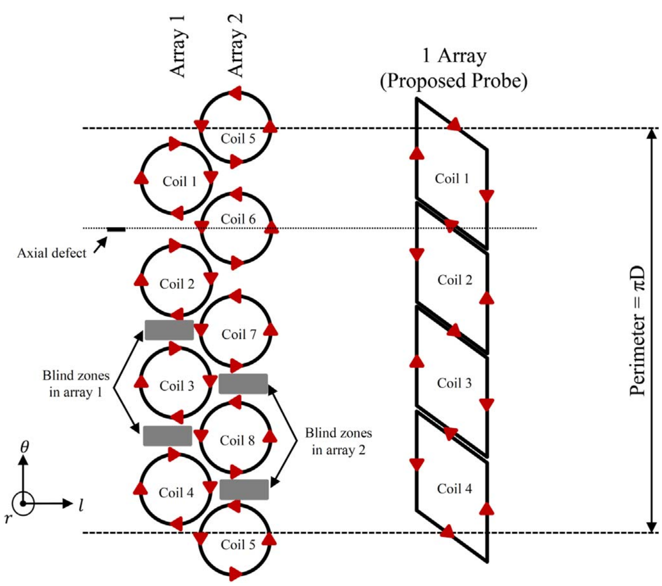

Fig. 2. Schematic of currents flow direction in circular spiral (left) and in trapezoidal spiral coils (right). The proposed EC probe with trapezoidal spiral coils avoids, with one array, the blind zones of the conventional probes.

especially in the reflection mode [9–13]. The planar spiral coils adhere to a conformable substrate, producing a very thin and flexible sensor allowing a greater proximity to the surface, reducing the lift off and increasing the sensitivity. Micro-fabrication techniques allow to produce reliable and repeatable cost effective sensors [14–17].

Commercial EC probes dedicated to the detection of circumferential defects are available but these are usually complex and expensive, and thus, a growing demand of reliable NDT probes remains [18]. A particular example of high demanding inspection consists of a round-in-square jacket profile in austenitic steel JK2LB [19], which constitutes the casing for the central solenoid conductor coils of the International Thermonuclear Experimental Reactor (ITER) [20]. These components require extremely high quality control, thus the need for probes with greater sensitivity to micro defects aligned with any orientation. Furthermore, the material has a very low magnetic permeability, similar to air ($\mu_r \approx 1$), and low electric conductivity, which is an added difficulty, since the perturbation of the magnetic field is lower.

This paper describes novel EC probe concepts. The probes were designed, manufactured, numerically simulated and experimentally validated in the inspection of the inner surface of austenitic steel jackets used in ITER, aiming to improve circumferential defects detectability when compared to commercially existing ones.

Different probes were proposed with different configurations in order to enhance the output signals and decrease the detectability threshold. These novel eddy current probes present a modular geometric configuration, allowing a vast combination between drive and pickup coils, cost-effective and suitable to produce by additive manufacturing. The proposed probes allow the detection of defects with any orientation on the inner surface of the tubular components and provide information on the defects axial and tangential position.

2. Probe design

A set of functional requirements for the probes was defined in order to increase the inspection reliability, compared to existing commercial EC probes. The new probes should: i) have a high sensitivity to detect small size defects with a very good signal-to-noise ratio when handled with conventional EC equipment; ii) be capable of detecting defects with any orientation (axial, tangential or oblique); iii) provide information on both axial and tangential position of the defect; iv) be easily customizable, economic and cost effective.

Fill factor was also considered in order to improve the response to potential cracks. The fill factor is the ratio between the cross section areas of the probe and the pipe. Therefore, the ideal fill factor is to be as close as possible to the unity. The fill factor of the manufactured probes was around 0.95. To meet these functional requirements five distinct probe configurations with different operating modes were designed, as summarized in Table 1.

The common feature of the probes is a linear array of planar trapezoidal spiral coils produced by Print Circuit Board (PCB) in a flexible substrate. This feature was selected for three main reasons: i) to maximise the proximity to the pipe inner surface and, hence, to the defect, allowing a superior sensitivity; ii) to provide a constant lift-off by simple adjustment to the pipe surface, since it is flexible; iii) and, finally, its simplicity to produce. In fact, the low production cost leads the sensor to be disposable and modular, that is, the same linear array pattern may be used together with different probe chassis and excitation coils, allowing different probe arrangements. The probe architecture is scalable, to different diameters, and its geometry can be adapted to exterior tube surfaces (including high temperature surfaces), involving the entire perimeter, or, in cases where the diameter is too big, a tangential section only.

The first configuration proposed (Probe #1), simply consists of an array of planar trapezoidal spiral coils on a flexible substrate around a cylindrical chassis as shown in Fig. 1. The sensitive plane is perpendicular to the *r* direction. The trapezoidal coils have a width of Δl, an angle between 2 consecutive coils of (α) about 45° (Fig. 1) and a number of elements determined by $\pi D/\Delta\theta$, where D [m] is the pipe perimeter and $\Delta\theta$ [m] is the length of each coil. The number of coils and their dimension in each array depends on the spatial resolution envisaged. Increasing the number of coils improves the spatial resolution. This configuration operates on absolute mode and aims at the detection of defects with any orientation.

Conventional EC probes composed of planar circular spiral coils present a common problem which is the existence of a blind zone in the interface between two consecutive sensitive coils. In this zone, the detection of defects becomes compromised or even impossible (Fig. 2). To overcome this problem, there is a need for a second linear array with an offset from the first array, to ensure that all the tangential positions of the pipe are covered by EC. An evident benefit of the proposed trapezoidal spiral coil configuration is that, a single array can avoid the blind zones and cover the whole pipe perimeter as well (Fig. 2). Nevertheless, it must be noticed that the density of eddy currents can