Innovative Flexible Eddy Current Probes for the Inspection of Complex Parts

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Abstract

Non Destructive Testing (NDT) using Eddy Current (EC) methods bring a solution to many industrial needs, concerning various applications and domains as nuclear or aeronautics. Nonetheless, when size of flaws decreases or inspection areas become hardly accessible, traditional probes based on classical winding coils turn out to be useless. Based on the use of new CIVA simulation tools, we have designed and optimized advanced EC probes, based on micro-coil arrays or magnetic sensors. These developments led to two innovative flexible EC probes respectively composed with 64 and 96 micro-coils etched on a flexible film which is set on a plugged head whose shape matches the geometry to be inspected. Embedded electronics increase Signal to Noise Ratio as demonstrated by several experimental cases. Second developments concern flexible magnetic sensors probes which are very attractive for deep defect detection at low frequency. The sensor operating point is monitored which allows the inspection of magnetic parts. Experimental testing on a ferromagnetic plate is shown.

Keywords: Eddy Current probes, flexible, array, magnetic sensor

1. Introduction

Eddy Current Technique (ECT) is a powerful method of inspection of metal parts, not only for the detection of small surface notches, but also for the detection of sub-surface defects. Recent EC array probes have demonstrated a fast and efficient control of large surfaces that makes this technique a good trade-off between ease of use, detection skill and cost. It has then a major stake for industrials.

This paper introduces the simulation platform CIVA [1] dedicated to Non Destructive Testing (NDT) and its recent developments. New modules have recently been added so that the design of arrays probes and the estimation of the sensibility of magnetic sensors are now possible. In a first part, the design and optimization of a large flexible EC probe using CIVA software is detailed. Then, several experimental results are shown and commented. In a second part, flexible EC probes based on magnetic sensors are presented. A specific electronic circuit has been developed to make the inspection of magnetic parts at low frequency possible. Its function is described and an experimental test reveals its efficiency.

2. Flexible Eddy Current Array Probes

The development of a new probe has to bring an answer to the specifications claimed by industrials. Mainly, two objectives are aimed to. First one concerns the spatial resolution. It is a critical parameter since it allows the detection of very small surface defects or even their sizing, with efficiency and quickness. For this, large arrays of sensitive sensors have to be achieved. A second challenge is the inspection of complex parts even when areas are hardly accessible. Therefore, studies have been carried out at CEA LIST to bring flexibility and modularity to the sensitive parts of the probe [2, 3].
2.1 Design of EC arrays probes using CIVA 10.0

The simulation platform CIVA dedicated to NDT is a powerful tool, not only for the design of EC probes, but also for the analysis of signals coming from simulation as from experience. Recent modules have been added so that it is now possible to simulate EC arrays based on circular or rectangular coils. These sensors can be put in one or more layers and defined as emitter, receiver or both, depending on their wiring. After been clustered, they are activated at various frequencies, within specific sequences. Figure 1a gives an example of an EC array design. Coils are put into two matrices (five rows, three columns) which are set on two layers. Coils on the first layer are defined as emitter when those on the second layer are receivers. Fifteen sequences are used to activate all the elements (composed with one emitter and one receiver) of the array. The sensitivity of the probe is evaluated using a through notch, 5mm long, 0.15 mm width, located into an Inconel mock-up plate which thickness is 1mm. This defect is orientated perpendicular to the scan direction. A screenshot of the calculated response of the defect at 1 MHz is given on Figure 1b.

Figure 1 : a) Design of a micro-coils EC array probe with CIVA 10.0 - b) Calculated detection of a through 5mm flaw into an Inconel mock-up

2.2 Development of a flexible and versatile EC array probe

Because of cost reduction, industrials claim for versatile EC probes that suit to a large spectrum of applications. In this context, a new EC probe based on micro-coils has been developed at CEA LIST with regards to this approach:

- versatile sensitive area: the number of the micro-coils, the spatial resolution and the size of the sensitive area is optimized regarding the application,

- versatile electronics: the number of Printed Circuit Boards (PCB) embedded into the probe depends on the number of the coils to be driven,

- versatile mechanic : the size and the shape of the sensitive area depends on the geometry of the part to be inspected.

In consequence, the advanced EC probe is composed with two parts. First one is called “body” and contains the PCBs. Its function is to drive the sensors and to amplify the received signals in order to guarantee an acceptable Signal to Noise Ratio (SNR). It also contains inserts to make possible the interface with a mechanical bench if necessary. The second part of the probe is called “head” and it consists in a flexible film on which the micro-coils are etched. Foam has been added under this film to bring flexibility. Its shape is designed so as to
fit the profile of the part. Another function of this foam is to keep the sensitive area in contact with the surface of the part which reduces lift-off noise and increases significantly SNR. So, for a given application or part to be inspected, a specific head containing the suitable number and arrangement of micro-coils can be developed when the body of the probe doesn’t have to be changed. Thanks to high density connectors the head is easily plugged to the body. Figure 2a is a photo of the EC probe when a head has been plugged and Figure 2b is a photo of a flat configuration head with 96 elements flexible film. Each element is composed with two micro-coils (emitter and receiver) which are set into matrixes 4 lines x 24 columns. The density of the sensors is increased by a staggered row arrangement that reduces the pitch to only 350µm and leads to a high spatial resolution with a large scan width (34mm).

The probe is driven by the MultiX-CF device provided by M2M Company and can be attached to a mechanical bench. Figure 3 is a photo of the measurement facilities.

Detection skill of the 96-elements EC probe has been evaluated at CEA LIST. The flexible film is set on a flat head, specially designed for the inspection of plates as well as pipes which
radius bends are large. The first experimental test, described on Figure 4, concerns a typical aeronautic application. The mock-up is an aluminum plate in which three surface notches have been electro-eroded. Characteristics of these defects are given in Table 1. The scan is a single line perpendicular to the flaws.

![Image](image1.png)

**Figure 4**: Inspection d’une plaque Aluminium avec la sonde CF 64 éléments

**Table 1**: Characteristics of the surface defects located into the Aluminum plate

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<tr>
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<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Depth (mm)</th>
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<tbody>
<tr>
<td>notch #1</td>
<td>1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>notch #2</td>
<td>1</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>notch #3</td>
<td>1</td>
<td>0.1</td>
<td>0.8</td>
</tr>
</tbody>
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The experimental CSCAN when the probe is driven at 1MHz is given on Figure 5. The X-axis corresponds to motion of the probe when the Y-axis is the response of every elements of the probe. Knowing the spatial arrangement of the coils into the matrix, the CSCAN can be reconstructed in real time. The three defects are detected with a good SNR and the amplitude of their signature depends on their depth, as expected. Furthermore, thanks to the high spatial resolution of the probe the length of the notches can be evaluated.

![Image](image2.png)

**Figure 5**: Detection of three surface notches into an Aluminum plate with the 96-elements EC probe

The second experimental test is representative of a nuclear application. The mock-up is an Inconel plate in which four surface notches have been electro-eroded and four flat-bottom
holes have been machined. A photo of the experimental setting is given on Figure 6 and characteristics of the defects are given in Table 2.

![Image](image-url)

**Figure 6**: Scan of the Inconel mock-up with the 96-elements EC probe

**Table 2**: Characteristics of the surface defects located into the Inconel plate

<table>
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<th>Length (mm)</th>
<th>Width (mm)</th>
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<td>notch #2</td>
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<td>0.2</td>
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<td>notch #3</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>notch #4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
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<table>
<thead>
<tr>
<th></th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
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</thead>
<tbody>
<tr>
<td>hole #1</td>
<td>0.2</td>
<td>1.25</td>
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<tr>
<td>hole #2</td>
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<td>0.2</td>
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<tr>
<td>hole #3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>hole #4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The scan is a single line and the experimental CSCAN when the probe is driven at 1MHz is given on Figure 7. The four notches are well detected even the smallest one which is only 100µm (notch #4). The four holes are also detected with a rather good SNR.
The experimental results obtained on planar mocks-up (Aluminum and Inconel) reveal the good performances of the flexible EC probe. Thanks to its high spatial resolution and good sensitivity, very small surface defects can be detected with accuracy. The manufacturing process of the flexible film technology is reliable and little dispersion has been observed between the elements of each films.

3. Eddy Current Probes Based on Magnetic Sensors

Magnetic sensors have become very attractive for some NDT applications [4]. Since their size can be reduced to few dozen of micrometers, the development of high spatial resolution EC probes is possible and well suited to the detection of small surface defects as it occurs in aeronautic domain. In this context, an EC probe based on a linear array composed with 96 Anisotropic Magneto Resistances (AMR) has already been developed at CEA LIST within the framework of a multi-partnership supported by the French National Research Agency [2, 3]. It has shown good efficiency in the detection of small surface defects. Furthermore, contrary to an equivalent winding coil, the sensitivity of a magnetic sensor remains constant when frequency decreases. Therefore, for the detection of sub-surface defects when low frequency is required because of skin depth effect, the use of such sensor is an asset.
3.1 Simulation of a magnetic sensor response to a defect using CIVA 10.0

For planar configurations, it is now possible to simulate the response of one or more magnetic sensor(s) to one or more defect(s). This new module is easy to use since the magnetic sensor is only defined by its axis detection and its sensitivity. Models have been validated by comparisons with experimental results. For instance, Figure 8 is a comparison of these data in the case of a surface flaw (10mm long, 0.1mm width and 0.93mm depth) located into an Inconel plate which thickness is 1.55mm. Thanks to a current foil, eddy currents are homogeneously induced along the [Oy] axis at 100 kHz. The detection axis of the magnetic sensor is perpendicular to the current foil so as to measure the [Ox] magnetic field component. After calibration, the good agreement between the two signals, from a quality and quantity point of view, is demonstrated.

![Figure 8: a) Configuration studied (CIVA 10.0) b) Comparison between simulation and experimental data, 100kHz](image)

3.2 Inspection of magnetic parts using a magnetic sensor

Because of the permeability of magnetic materials, the inspection of magnetic parts has to be performed at low frequency. In such domain, magnetic sensors have proven good sensitivity and their use is promising [3]. Nonetheless, a special feature of magnetic sensor is their sensitivity to residual magnetic field that can occurs into a magnetic part. An experience has been realized to underline this problem. The scheme on Figure 9a describes it. A little circular magnet has been horizontally put on the surface of a ferromagnetic plate (16MND5) and then removed. An EC probe composed with one emitter (a standard winding coil) and one receiver (a magnetic sensor) is used to scan the mock-up in which two holes are located. The characteristics of the defects are given in Table 3.

![Figure 9: a) Modelisation of an EC probe based on a magnetic sensor with CIVA software - b) Detection of a 10mm flaw into an Inconel plate : comparison between experimental and simulated data](image)

Table 3: Characteristics of the defects into the 16MND5 plate

<table>
<thead>
<tr>
<th></th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
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</thead>
<tbody>
<tr>
<td>Hole #1</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>Hole #2</td>
<td>4</td>
<td>2</td>
</tr>
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</table>

The experimental CSCAN obtained at 70 kHz is given on Figure 9b. As expected, not only both holes are detected but also the residual magnetic field in the material due to the magnet. For an unknown part, such signature could be interpreted as a third defect or could hide the response of an adjacent defect. That the reason why a specific PCB has been studied and
developed at CEA LIST in order to decrease this fake signal. The experimental CSCAN obtained with the use of the control loop is given on Figure 9c. The signature due to the residual magnetic field has almost disappeared. Besides, both holes are better detected and SNRs have increased. The electronic circuit has proven its efficiency and the inspection of magnetic parts using magnetic sensor EC probe is now possible.

4. Conclusions

New tools have been recently added to the NDT software CIVA 10.0. They give keys to defining the most suitable parameters of array coils to a given application and bring a help for the analysis of magnetic sensors response to defects. Using these new modules, flexible EC array probes have been optimized in order to develop a versatile probe. Its head can be removed from its body so that it can be changed depending on the application. For this, the shape of the flexible sensitive area and the density of sensors are defined to suit the geometry of the inspected part. Several PCB embedded into the probe itself allow a good amplification of the received signals that improves SNR. Experimental CSCANs obtained when using the flexible 96-elements EC probe have demonstrated its good performance in the detection of small surface defects.

On the other hand, multi-elements and flexible EC probes based on magnetic sensors have been developed at CEA LIST. Because of its large bandwidth, this technology turns out to be very attractive for the inspection of ferromagnetic parts when low frequency is required. A specific electronic circuit has been integrated so as to erase the signature of a residual magnetic field that may occur in such parts. Experimental testing has been performed and shows its efficiency.
References


