EXCITING COIL OPTIMIZATION CRITERIA FOR EDDY CURRENT DETECTION OF SMALL CRACKS UNDER FASTENER HEAD

T. BOUCHALA [1], N. BENHADDA [2], B. ABDELHADI[3] and A. BENOUDJIT
[1] Electrical Engineering Department, Kasdi Merbah University, Ouargla, Algeria.
[2] Electrical Engineering Department, Ziane Achour University, Djelfa, Algeria.
[3] Electrical Engineering Department, El-Hadj Lakhdar University, Batna. Laboratory of Electric Traction Systems – Batna (LSTE - Batna), Alegria.

bouchala.tarek@univ-ouargla.dz , *nabil_benhadda@yahoo.fr*, *abdelhadi3b@yahoo.com*, *benoudjit@yahoo.fr*

Abstract – *The aim of this paper consists of presenting optimization criteria of coil dimensions and the exciting field frequency in order to improving eddy current probe sensitivity for small and deep cracks under fasteners. To accomplish this task, we have studied the influence of coil inner radius, coil height and exciting frequency on probe sensitivity. Then, an algorithmic searching technique is applied to determine the optimal values of the previous parameters. Hence, the obtained results have revealed that the optimum inner radius corresponds exactly to the fastener head outer radius. Furthermore, it has been noticed that as well as the coil height is reduced while keeping the same number of turns, the probes sensitivity increases. Indeed, the use of stacking flat micro-coils is well adapted. In addition, the calculation of the optimum values of the frequency demonstrate that this parameter depend relatively on the defect position, its radial and vertical depth.*

Keywords: *Cracks Under Fasteners; Probes Sensitivity; Coil Dimensions; Optimization Procedure; Eddy Current Testing.*

1. Introduction

The detection of cracks under fasteners (CUF) is an important problem in nondestructive evaluation of multilayer aircraft skin structures [1]. Eddy-current nondestructive testing (EC-NDT) are generally used in the inspection of aircraft skin for the detection of subsurface cracks. However, detection of deep or second and third layer CUF is challenging because the weak eddy-current (EC) signal due to a subsurface crack is dominated by the strong signal response from the fastener [2-3]. So, an optimized sensor must induce the greatest eddy currents density near the crack, in order to obtain the greatest sensor response [4]. Detection and the characterization of defect existing in the material as a loss of material. However, other defects can appear this can be done by using adapted finite element package with parameters studies. In our study, the considered parameters are successively the coil inner radius, coil height and the exciting field frequency.

Qualitatively, the optimal value of each parameter corresponds to the better interaction between the sensor and the defect. Quantitatively, the optimum value is obtained when the impedance variation, caused by the presence of the defect is maximal [5]. After this investigation, we shall give the criteria to be considered by designers to improve the sensors sensitivity for small cracks under fasteners. This study can be extended to pulsed eddy current systems in order to complete previous work, in which some parameters are studied, such as pulse widths that give different depth information based on the frequency components associated with different duty cycles [6].

2. Geometry of the Studied Device

Fig. 1 shows the geometry of a sample part. The absolute probe made of copper operates above three aluminum layers riveted with fastener and made of titanium. The exciting current is sinusoidal with a frequency of 1.6 kHz.

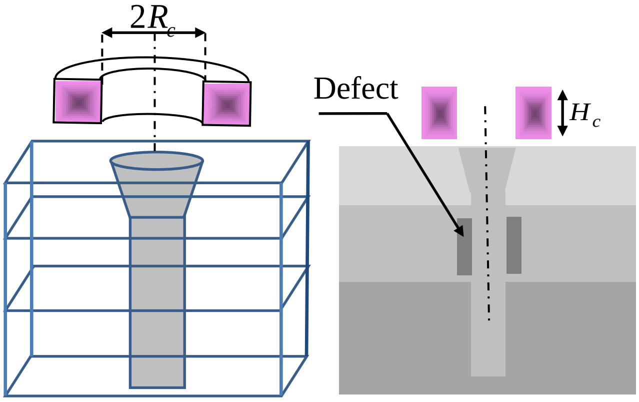


Fig.1 Geometry of the studied device and the studied

The geometrical and physical characteristics of the system to be simulated and studied are given on Table 1.

Table 1. Characteristics of the studied device

Coil	Inner radius (R_c) Width (W_c) Height (H_c)	[0.1 mm, 15 mm] 4 mm 3.46 mm
Layer 1	Thickness Electric conductivity	4 mm 17 MS/m
Layer 2	Thickness Electric conductivity	4 mm 17 MS/m
Layer 3	Thickness Electric conductivity	2.25 mm 17 MS/m
Rivet	Electric conductivity Foot height Foot radius Head height Head radius	2.34 MS/m 9.125 mm 3.175 mm 1.075 mm 6 mm
Defect	Height Width	4 mm 2.65 mm

3. Finite Element Modelling

The differential equation governing eddy current phenomena in regions that include conducting and magnetic material can be written as follow:

$$\frac{1}{\mu}(\nabla \times \nabla \times A) = J_s - \sigma \frac{\partial A}{\partial t} \quad (1)$$

Where μ, A, J and σ are the magnetic permeability (H/m), magnetic vector potential (Wb/m), applied current density vector in the coil (A/m^2) and the electrical conductivity (MS/m) respectively.

In the case of the single frequency $(\omega(rad/s))$ continuous wave, as is the case in many eddy current testing, Equation (1) can be reduced to:

$$(\frac{1}{\mu})\nabla^2 A = -J_s + j\omega\sigma A \quad (2)$$

The solution to this linear diffusion equation for the sinusoidal steady state condition can be obtained in a terms of A by solving Equation (2) with appropriate boundary conditions. From the values of A, one can obtain any observable electromagnetic phenomena such as coil impedance changes, energy dissipation, flux density, etc....

Many practical eddy current NDT geometries are axisymmetric as the excitation coils are circular. An absolute or differential probe over a conducting plan, a feed through probe in a conducting tube, and an encircling probe system around a conducting rod are some of the geometries satisfactorily analyzed in a simplified cylindrical coordinates system (r, θ, z). In this system, both J_s and A have components only in the positive θ direction which means that they are functions of r and z only. Hence, in the case of axisymmetric geometries, Equation (2) can be reduced to:

$$\frac{1}{\mu}(\frac{\partial^2 \vec{A}}{\partial r^2} + \frac{1}{r}\frac{\partial \vec{A}}{\partial r} + \frac{\partial^2 \vec{A}}{\partial z^2} - \frac{\vec{A}}{r^2}) = -\vec{J}_s + j\omega\sigma\vec{A} \quad (3)$$

The finite element method does not offer a solution to the diffusion equation directly [7]. Instead, the solution is obtained at discrete points (nodes) in the solution region by formulating an energy functional equivalent to Equation (3), and minimizing it with respect to an approximate function space.

4. Sensor Impedance

There are many expressions in NDT to calculate the complex impedance of an absolute probe. In our case, we have chosen the following expression, [10]:

$$Z_{probe} = -\frac{j2\pi\omega N_C}{I_s}\sum \mathrm{r_c}\,\Delta\,\mathrm{A_c} \quad (4)$$

Where Δ is the area of the elements.

5. Optimal Parameters of Coil Dimension and Exciting Field Frequency

The main goal of ECTP design is to obtain a probe featuring good sensitivity and minimal volume. This could be achieved by optimizing coil dimensions [3]. In the following sections, we shall elaborate the calculation of the optimum parameters for which the defect signature is more important. To do this, we have developed a finite element code in Matlab software, permitting to calculate all electromagnetic quantities such as the vector magnetic potential, the induced currents and the sensor impedance. In all situations, the optimal parameter corresponds to the maximal impedance variation. The first step to design a "good" probe is therefore to optimize the coil and the current that create eddy current in order to have a "flaw signal" as important as possible. The parameters to optimize, for the given coil turns number are:

- Coil inner radius (R_c)
- Coil height (H_c)
- Frequency (f)

5.1 Optimal Coil Inner Radius

The optimization of the frequency and the coil parameters is undertaken by creating an optimization interval for each parameter. To determine the optimal inner radius, we fixed the other geometric parameters and varied the inner radius from 0.1mm to 15mm. The corresponding impedance variation is calculated while using FEM that we have implanted in Matlab environment as depicted in Figure (2). It is worth mentioning that the defect outer radius is smaller than that of the rivet head (hidden defect).

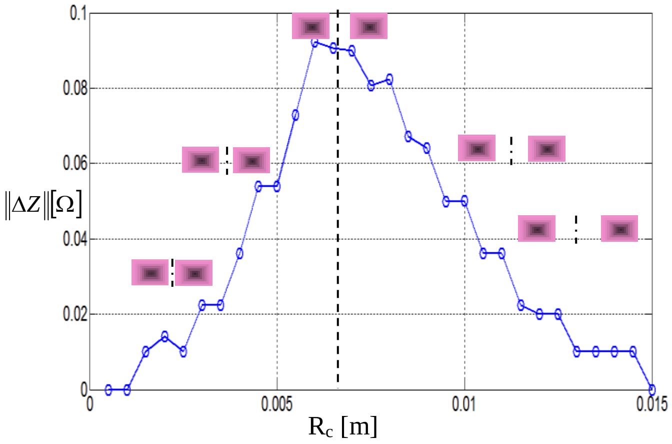
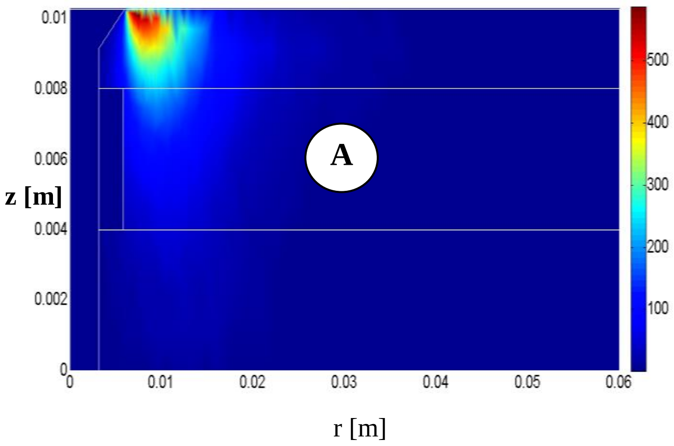


Fig .2 Impedance variation amplitude according to coil inner radius

In order to find an adequate interpretation of the previously obtained results, we have presented the distribution of the induced eddy current density, in the riveted materials sections, for the optimal and the extreme values of coil radius as depicted in Figure 3.



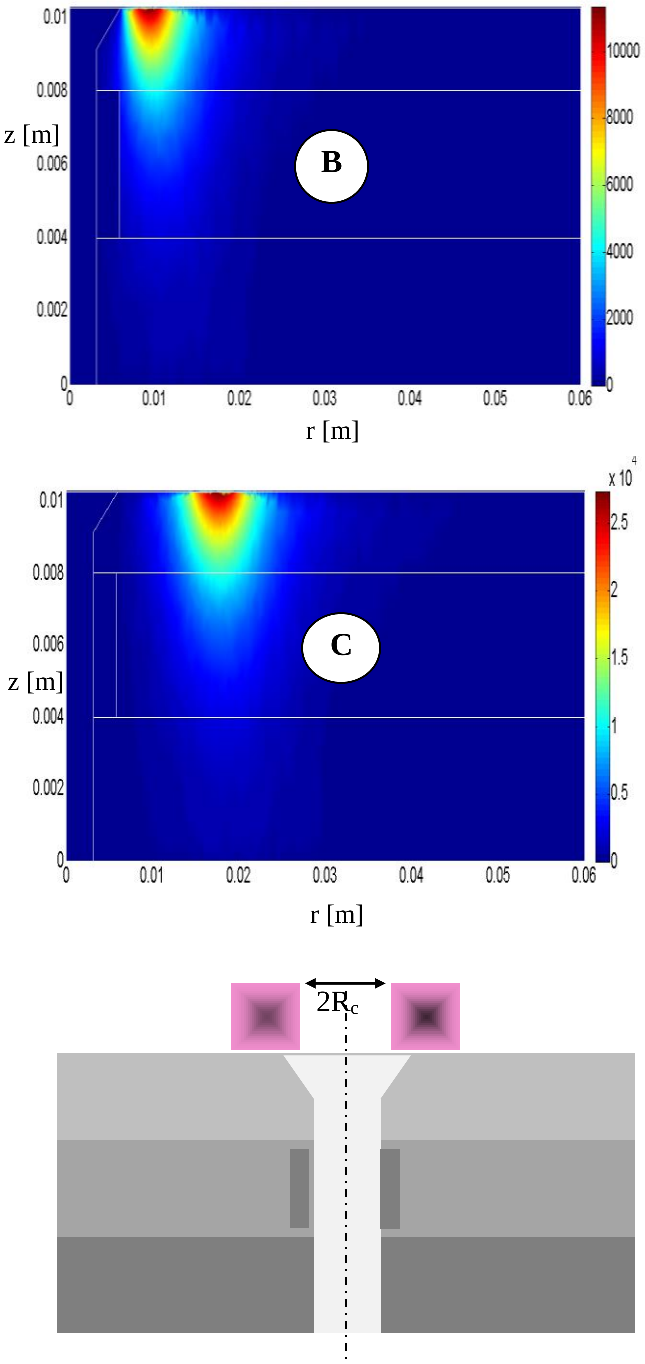


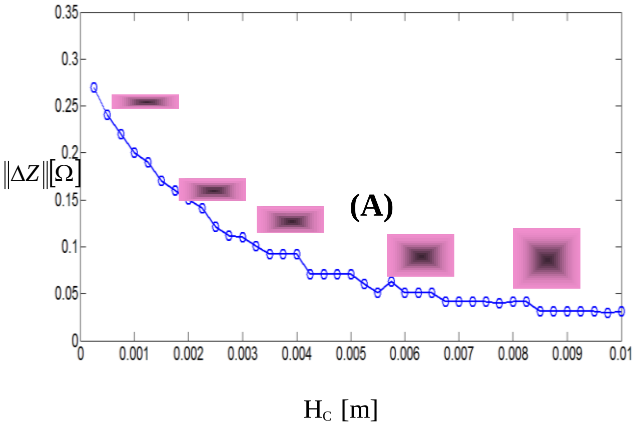
Fig. 3 Induced current density for three values of coil radius. (A : $R_c = 0.5mm$), (B : $R_c = 6mm$) and (C : $R_c = 15mm$).

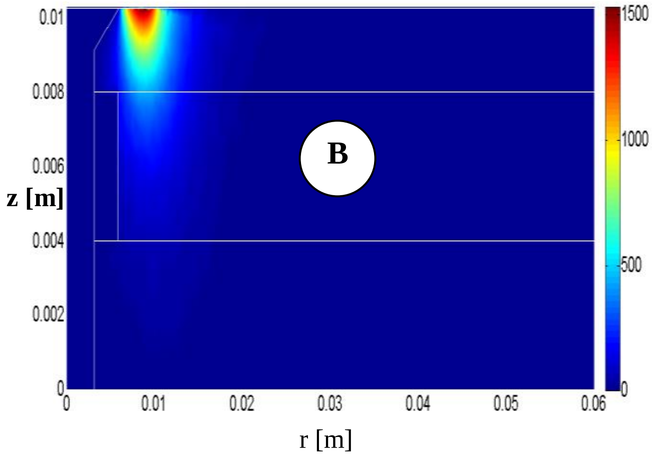
According to the results shown in Figure 3, one can notice that the distribution of the induced currents varies from one case to another. In Figure 3.A, the induced currents are disrupted by the rivet that presents an obstacle for the creation of eddy currents in neighboring zone of the defect [4]. Therefore, the latter doesn't alter greatly the induced currents. Therefore, the variation of the corresponding impedance remains weak.

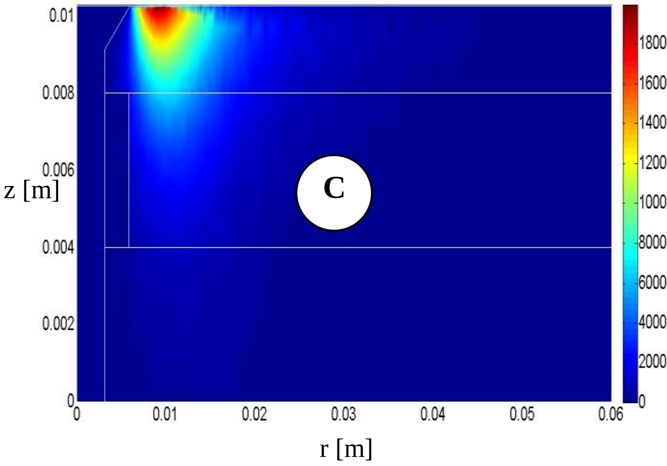
On the other hand, in Figure 3.C where the coil radius is important, the zone where the induced currents are intense is far from defect. Therefore, the impedance variation remains too weak. The optimal radius is =0.004mm (Figure 3.B). This one corresponds precisely to the rivet head radius. In this case, the defect disrupts importantly the induced currents; and the variation of impedance is maximal. After having determined the optimal coil radius, we shall proceed to search the optimal operating frequency.

5.2 Optimal coil height

To determine the optimal height, we have introduced in the simulation the optimal parameter quantities. Then, by varying the coil height from 0.25mm up to 10mm and we have calculated the corresponding impedance variation. The results are shown in Figure (4).







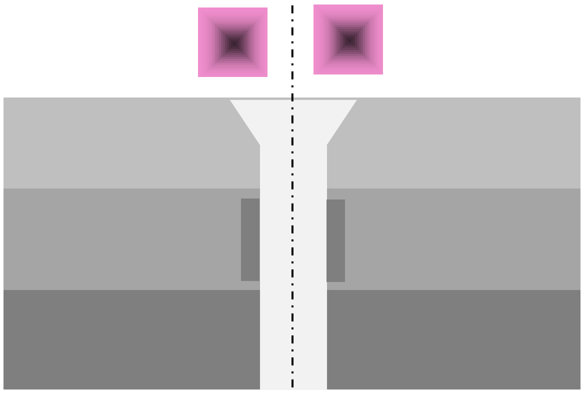


Fig .4 (A): Impedance variation amplitude with coil height. (B) and (C): Distribution of the induced current density for $H_c = 0.25mm$ and $H_c = 10mm$.

Through the results shown in Figure (4), one can observe that the amplitude of the defect signature decreases when the height increases. Therefore, the use of coil with a high spires density according to the vertical axis is required. Practically, this can be achieved by assembling flat micro-coils which allows a high special resolution and sensitivity comparatively to conventional coils [11-12].

5.3 Optimal exciting field frequency

Frequency inspection in eddy current testing is crucial to detecting flaws. At the optimum frequency of testing, the crack sensitivity reaches the maximum [5]. To determine the optimal frequency, we vary the frequency in a large range (from 50Hz to 20kHhz); then we calculate the impedance variations caused by the defect (Figure 5). The geometric features of the coil are those used previously, but the inner radius is set to its optimum value calculated in the above section.

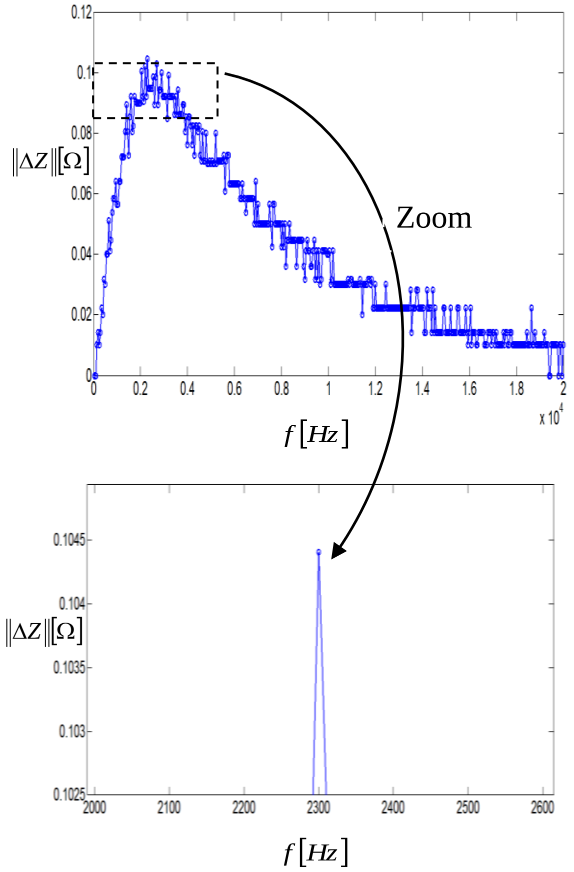
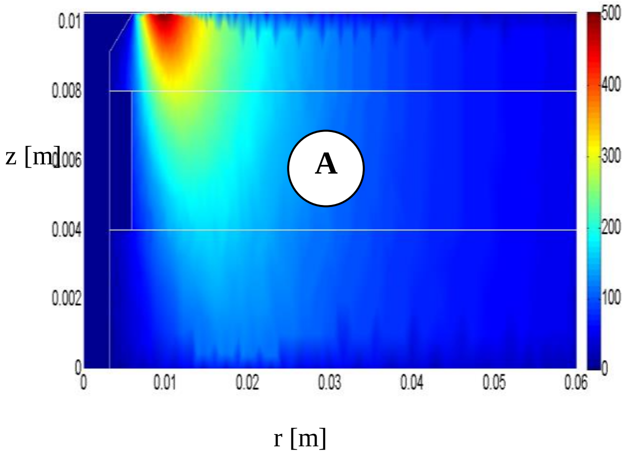


Fig.5 Impedance variation amplitude according to exciting field frequency

To illustrate the obtained results, we have shown the distribution of the eddy current density in the riveted material section for the extreme and the optimal values of frequency (Figure 6).



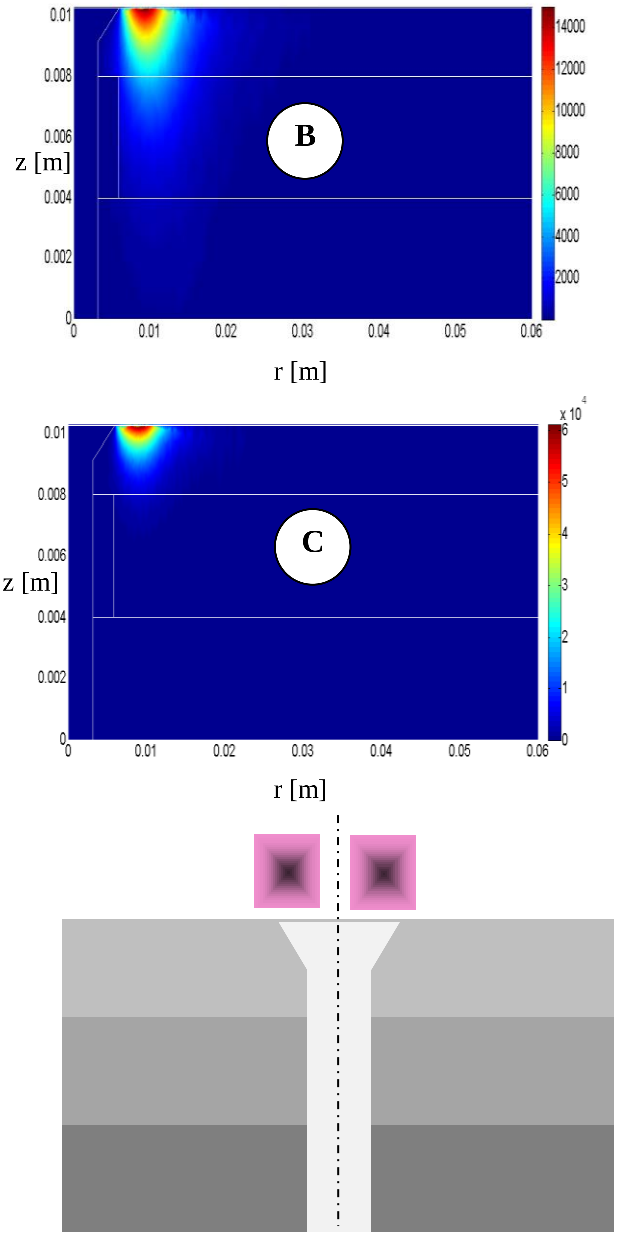


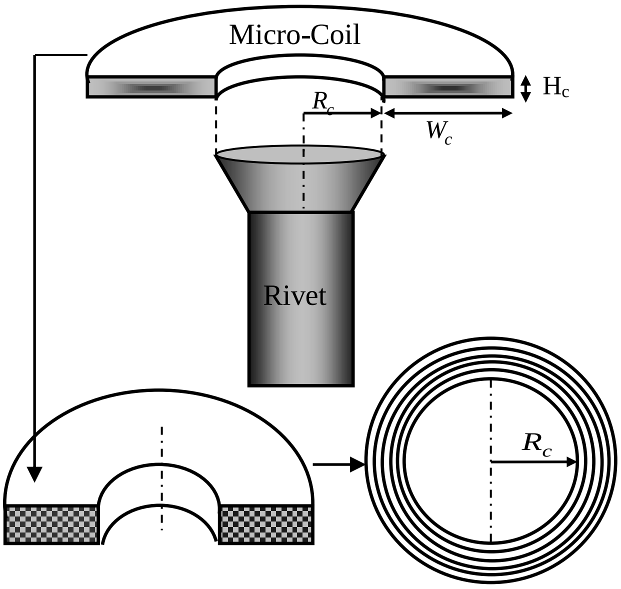
Fig. 6 Induced current density for three frequencies. (A : $f = 50Hz$), (B : $f = 2.3kHz$) and (C : $f = 20kHz$).

According to the results shown in Figure (6), one can observe that the distribution of the induced currents varies from one frequency to another. In Figure (6.A), the induced currents are penetrated in all layers, but their amplitude is weak. Therefore, the defect alters less magnetic field lines. Therefore, the corresponding impedance variation remains weak too. On the other hand, in Figure (5.B) when the frequency is increased, the induced currents are focused to the surface; therefore, penetrate less in the flawed layer. Thus, the amplitude of the impedance variation remains feeble. According to

Figure (5.C), the optimal frequency is 2300Hz. In this case, the defect disrupts more the induced currents and the impedance variation becomes high.

Therefore, the designer of the sensors for high sensitivity detection of cracks under fasteners must take into consideration the following backgrounds:

- The coil inner radius must be precisely equal to rivet head radius as shown in Figure (7).
- The coil height (H_c) must be reduced enough in order to increase the number of turns according to the vertical axis sand the exciting current density must be raised as much as possible. This can be realized by stacking in series flat micro-coils
- The exciting field frequency (f) depend on defect depth as well as on the physicals and geometrical characteristics of the system.



Stacking of flat micro-coils

Flat micro-coil

Fig. 7 Optimal coil design

6. Conclusion

Eddy current non-destructive testing (EC-NDT) methods are used widely in aerospace, power and transportation industries where the cost of critical component failure can be high. This technique is one of the most extensively used for inspecting electric conductive materials at very high speeds because it does not require any contact between the test piece and the sensor [13-15]. Nowadays, several works have been fulfilled on the detection of hidden defect under rivet by using eddy current techniques [4-5]. But, only a small number of works have elaborated the optimization of sensor in order to improve their sensitivity to this kind of defect. In this article, we have presented criteria taking into consideration for the design of sensitive sensors destined for the detection of small cracks under fastener. Three parameters have been studied: the exciting field frequency, the inner radius and the coil height. In essence, the obtained results have revealed that the coil inner radius has to be precisely equal to rivet head radius. Also, the coil height has to be sufficiently reduced and the coils density has to be increased as much as possible. This can be realized by stacking in series flat micro-coils. On the other hand, the optimal values of the exciting field frequency depend on defect depth as well as on the physicals and geometrical characteristics of the system; therefore, knowing the interval variation of defect dimension, the optimal values of this parameter can be deduced. As a future work, we intend to extend this study for pulsed eddy current systems [6].

7. References

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