Non-destructive rapid defect testing around curved head rivets without displacement of eddy current sensors

Teste não destrutivo rápido de defeitos ao redor de rebites com cabeça curva sem deslocamento dos sensores de corrente de Foucault

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Merwane Khebal
PhD Student in Electrical Engineering
Institution: University of M'sila
Address: M'sila, Algeria
E-mail: merwane.khebal@univ-msila.dz

Abdelhak Abdou
PhD in Electrical Engineering
Institution: University of Batna
Address: Batna, Algeria
E-mail: abdelhak.abdou@univ-batna2.dz

Tarik Bouchala
PhD in Electrical Engineering
Institution: University of M’sila
Address: M’sila, Algeria
E-mail: tarik.bouchala@univ-msila.dz

Abderrahmane Aboura
PhD Student in Electrical Engineering
Institution: University of M’sila
Address: M’sila, Algeria
E-mail: abderrahmane.aboura@univ-msila

Abdelhadi Bachir
PhD in Electrical Engineering
Institution: University of Batna
Address: Batna, Algeria
E-mail: b.abdelhadi@univ-batna2.dz

Guettafi Amor
PhD in Electrical Engineering
Institution: University of Batna
Address: Batna, Algeria
E-mail: a.guettafi@univ-batna2.dz
ABSTRACT
In the field of aeronautics, it is essential to ensure the structural integrity of aircraft components. Non-destructive testing (NDT) plays a crucial role in ensuring the safety and reliability of structures used in aeronautics as it enables the detection of defects and imperfections without damaging the inspected parts. Domed head rivets are commonly used in aeronautics to assemble multilayer structures due to their strength and ability to maintain the structural integrity of aircraft. However, inspecting these assembly areas can be challenging and presents unique challenges in terms of non-destructive testing due to the curved surface of the rivet, resulting in lift-off variation during surface scanning and a modification of the trajectory of eddy currents near the rivet. This can lead to changes in the response of eddy currents, complicating the accurate interpretation of test results. In recent years, researchers have focused on developing advanced eddy current testing methods to detect defects in complex structures, such as those found in aeronautics. In this work, we propose a promising solution to address both the shape of the rivet and the probe displacement issue during testing. We have developed a model based on the finite element method (FEM) using COMSOL Multiphysics for non-destructive testing through 3D imaging using a matrix of multiplexed multi-element eddy current sensors distributed over multiple layers around the rivet without the need for the displacement of this matrix and capable of adapting to the variation in the diameter of the domed head rivet. The non-displacement of the sensors eliminates parasitic signals that can lead to errors in the interpretation of obtained signals, and the multiplexed powering of the sensors eliminates the mutual inductance effect between adjacent coils.

Keywords: eddy currents, multilayers, riveted structures, non-destructive testing imaging, multi-element, finite element method.

RESUMO
No campo da aeronáutica, é fundamental garantir a integridade estrutural dos componentes das aeronaves. Os testes não destrutivos (END) desempenham um papel crucial para garantir a segurança e a confiabilidade das estruturas utilizadas na aeronáutica, pois permitem detectar defeitos e imperfeições sem danificar as peças inspecionadas. Rebites de cabeça abaulada são comumente usados na aeronáutica para montar estruturas multicamadas devido à sua resistência e capacidade de manter a integridade estrutural das aeronaves. No entanto, inspecionar essas áreas de montagem pode ser difícil e apresentar desafios únicos em termos de controle não destrutivo devido à superfície curva do rebite, que causa variações no levantamento durante a varredura superficial e uma modificação na trajetória das correntes de Foucault nas proximidades do rebite. Isso pode levar a mudanças na resposta das correntes de Foucault, o que dificulta a interpretação precisa dos resultados do teste. Nos últimos anos, os pesquisadores têm se concentrou no desenvolvimento de métodos avançados de controle por correntes de Foucault para detectar defeitos em estruturas complexas, como as encontradas na aeronáutica. Neste trabalho, propomos uma solução promissora para os problemas relacionados tanto com a forma do rebite quanto com o problema do deslocamento das sondas durante a inspeção. Desenvolvemos um modelo baseado no método dos elementos finitos (MEF) com o COMSOL Multiphysics para controle não destrutivo por meio de imagens 3D usando uma matriz de sensores de correntes de Foucault de múltiplos elementos.
Multiplexados distribuídos em várias camadas ao redor do rebite sem a necessidade de deslocar esta matriz e capaz de se adaptar à variação no diâmetro do rebite de cabeça abaulada. O não deslocamento dos sensores permite eliminar os sinais parasitas que podem induzir erros na interpretação dos sinais obtidos, e a alimentação multiplexada dos sensores tem o efeito de eliminar o efeito de mútua indutância entre bobinas adjacentes.

**Palavras-chave:** correntes de Foucault, multicamadas, estruturas rebiteadas, imagem de teste não destrutivo, multi-elemento, método dos elementos finitos.

1 INTRODUCTION

Assessing structural integrity to detect potential damage is crucial within aircraft maintenance systems. Presently, common diagnostic approaches predominantly rely on visual inspections and non-destructive testing (NDT) methods (Bennoud and Zergoug, (2014); Chady et al. (2021b)). These techniques align with damage tolerance or integrated safety methodologies (Chady et al. (2021a)), which presuppose the potential occurrence of a failure mode. (García-Martín et al. (2011); Uemura et al. (2019).). One of these non-destructive testing methods that has gained importance in the aerospace industry is the use of multiplexed multi-element eddy currents for detecting defects around rounded head rivets in multi-layer structures (Bouhlal et al. (2024); Fahr (2013); Shao et al. (2023)).

Multi-layer structures are widely used in industries, particularly in aircraft and spacecraft construction, where layers are assembled through riveting operations. Riveting involves joining pieces using rivets, with each layer pre-drilled with a hole allowing the rivet shanks to cross through. It is a permanent component, meaning it cannot be disassembled without breaking its fixation. Under the functioning of the riveted structure, various external factors are encountered, such as low temperature, high pressure, and sound vibrations, with the latter causing damage and corrosion. Typically, these issues are concentrated around the rivets (Bouzidi et al. (2012); García-Martín et al. (2011)).

One of the applications of eddy current testing (ECT) in aerospace is the structural inspection of multi-layer riveting (e.g., aircraft skins). The inspection of these structures aims to detect defects near the rivets that may be caused
by the mechanical stresses they are subjected to (Abdelhak Abdou (2019); Uchanin (2020, 2021)). Countersunk rivets are commonly used in aeronautics to assemble multi-layer structures due to their strength and ability to maintain the structural integrity of aircraft. However, inspecting these assembly areas can be challenging due to the opacity of the rivets and the presence of multiple layers of materials (Abdou et al. (2019); Janovec et al. (2019a)).

Recent progress in electronics has facilitated the emergence of innovative inspection methods, including multi-element eddy current (EC) testing. Compared to conventional approaches like dye penetrant inspection and magnetic particle inspection, these techniques offer improved reliability and repeatability in surface inspections (Uchanin (2020); Vaverka et al. (2022)). The flexibility to customize coil configurations and sequencing patterns empowers users to tailor the acquisition process to their specific requirements. Furthermore, through the utilization of multiple active elements and advanced data processing capabilities, multi-element EC solutions facilitate quicker inspections, often necessitating less surface preparation (Uchanin (2023)).

The eddy current array (ECA) inspection technique is based on the same general principles as conventional eddy current (EC) testing. Indeed, it involves generating a magnetic field in a conductor inducing currents that provide information about the health of the inspected component. However, with ECA, the field generation and measurement are performed using one or more electronically activated coils in a given pattern repeated across all elements/coils comprising the sensor. This is known as sequencing (the timing of each pattern activation). This allows for adjusting the testing method to the application by dedicating the pattern to the tested material and the sought-after defects, offering broader coverage with increased imaging capabilities for faster and less operator-affected inspection (Janovec et al. (2019b); Uchanin (2023); Xie et al. (2015)). The technology of multi-element eddy current sensors involves inducing magnetism in conductors that provide information about the electrical current health of the tested component. However, the field generation and measurement are performed using one or more electronically activated coils in a given pattern repeated across all elements/coils comprising
Recent research highlights the use of advanced eddy current non-destructive inspection (NDI) techniques for ensuring aircraft safety and efficiency. In one study (Janovec et al. (2020)), scientists employed eddy current-based NDI to identify simulated corrosion in aircraft aluminum riveted joints using a defectoscope with an ECA measurement module and suitable probes. Another study (El-Kahina and Kamel (2021)) investigated stress field impacts near cracks in aerospace-grade aluminum 7075-T6, using an enhanced eddy current technique with specialized probes. Additionally, a study (Wang et al. (2023)) focused on cracks in riveted aircraft components caused by stress concentration in holes, proposing a solution using a far-field eddy current detection probe, demonstrating effectiveness in detecting hidden defects.

Our objective is to propose an innovative and rapid solution for the detection of defects around domed head rivets, and whose signal obtained by 3D eddy current imaging for defect characterization will not be affected either by the change in lift-off due to the shape of the rivet or by the parasitic signal due to sensor displacement. These images thus facilitate the interpretation of data and the detection of potential defects. Using the finite element method (FEM) in COMSOL Multiphysics, we have developed a model for a non-destructive inspection system using a matrix of multiplexed multi-element eddy current sensors to eliminate the mutual inductance effect between coils. This sensor matrix, distributed over multiple layers around the rivet, forms a circular array surrounding the assembly area. Our approach eliminates the need to physically move the sensor matrix, and it adapts to variations in rivet diameters. These advancements promise to significantly improve the efficiency and accuracy of aerospace structure inspection, advancing reliable practices in this critical field.

2 SYSTEM DESCRIPTION

The proposed multi-layer riveted structure (Figure 1) sets a standard in this domain, drawing its geometric and physical attributes from an authentic industrial model within the sector. The simulation of any electromagnetic
system mandates an understanding of all the physical and geometric properties across various regions. Table 1 illustrates the physical and geometric parameters of the investigated system.

![3D Geometry of the System Under Study](image)

**Table 1: Physical and geometric parameters.**

<table>
<thead>
<tr>
<th>Multilayer structure</th>
<th>Rivet</th>
<th>coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length L = 100 mm</td>
<td>Hc = 1.88 mm</td>
<td>Hf = 5.33 mm</td>
</tr>
<tr>
<td>Width L = 70 mm</td>
<td>Rt = 6 mm</td>
<td>· · ·</td>
</tr>
<tr>
<td>Layer 1 thickness: h1= 2.5 mm</td>
<td>· · ·</td>
<td>· · ·</td>
</tr>
<tr>
<td>Layer 2 thickness: h2= 4 mm</td>
<td>Rr2 = 3.175mm</td>
<td>· · ·</td>
</tr>
<tr>
<td>Layer 3 thickness: h3= 4 mm</td>
<td>· · ·</td>
<td>· · ·</td>
</tr>
<tr>
<td>Lift = 0.5*10^-3 mm</td>
<td>· · ·</td>
<td>· · ·</td>
</tr>
</tbody>
</table>

**Geometrics Properties**

| Conductivity | σ = 1*10^6 (S/m) | σ = 60*10^6(S/m) |
| Physical properties | | |

Source: Authors.

2.1 MESH OF THE PROPOSED MODEL

Each volume comprising the study domain needs to be discretized using geometric elements that create a mesh on the nodes where physical quantities will be numerically determined. COMSOL Multiphysics offers various types of discretization elements, including tetrahedral, hexahedral, or prism elements. The selection of element type influences the number of degrees of freedom needed for the numerical solution of the problem. In our case, we opted for a mesh with tetrahedral elements because this option facilitates the automatic meshing of different geometries, as illustrated in Figure (4).
3 MATHEMATICAL MODEL

Maxwell's equations serve as the mathematical basis for addressing electromagnetic eddy current (EC) phenomena using the finite element method (FEM). This approach allows for the calculation of the sensor's eddy current response. The magnetic vector potential, electric and magnetic fields, and pointing vectors are typically utilized as parameters to solve the field equations (Abbassi et al. (2020); Bennoud and Zergoug (2014); Yating et al. (2008)). The quasi-stationary Maxwell equations are as follows:

\[ \nabla \times H = J_s \quad (1) \]

\[ \nabla \times E = -\frac{\partial B}{\partial t} \quad (2) \]

\[ \nabla \cdot D = 0 \quad (3) \]

\[ \nabla \cdot B = 0 \quad (4) \]

The relationships that describe the material properties concerning electromagnetic fields are outlined below:
\[ \vec{B} = \mu \vec{H} \] (5)

\[ \vec{J} = \sigma \vec{E} = -\sigma \frac{\partial \vec{A}}{\partial t} \] (6)

In Equations 1 to 4, H, E, B, D, J, and t represent the magnetic field, electric field, magnetic flux density, electric flux density, coil current density, and time, respectively (Rosell and Persson (2012); Salama et al. (2021)).

\[ B = \nabla \times A \] (7)

The relationship between the electric field and the magnetic vector potential can be established as follows:

\[ E = -\nabla \Phi - \frac{\partial A}{\partial t} \] (8)

The three-dimensional electrodynamics equation is expressed as follows:

\[ \frac{1}{\mu} (\nabla \times \nabla \times A) + \sigma \frac{\partial A}{\partial t} = J_s \] (9)

\[ \nabla \sigma \left( \frac{\partial A}{\partial t} + \nabla V \right) = 0 \] (10)

The eddy current problem is mathematically expressed using the equation in terms of the magnetic vector potential (A) and the electric vector potential (V) as follows:

\[ \nabla^2 A + K^2 A = -\mu J_{Excitation} \] (11)

With:

\[ K^2 = -\omega \mu (j \sigma + \omega \varepsilon) \]

\( \omega \) is the angular frequency of the excitation current.

By determining the magnetic energy stored throughout the space and the
joule losses in the conductor for both the defect-free (Es) and defective (Ed) scenarios, we can derive the alteration in sensor impedance (Ed).

\[ Z = R + jX \]

is the impedance formula, where R and X are determined using the following formulas:

\[ E_{joule} = \int_{\text{conductor}} \frac{1}{\mu} (J) \, dv ; \quad \Delta R = \frac{1}{I^2} \left( E_{joule}^d - E_{joule}^s \right) \quad (12) \]

\[ E_{mag} = \frac{1}{2} \int_{\text{space}} \frac{1}{\mu} (BB) \, dv ; \quad \nabla X = \frac{2\omega}{I^2} \left( E_{mag}^d - E_{mag}^s \right) \quad (13) \]

4 RESULTS AND DISCUSSION

4.1 INDUCED CURRENT

To verify the simulation model, we must first compare the results obtained from the induced currents in the aluminum plate for a single coil at different positions of the sensor in the first layer and away from the defect, then near the defect, and then in other coil layers, as shown in Figure (3).
Figure 3. Variation of induced currents depending on coil position.

In the first layer, we observe a decrease in the maximum induced currents in the presence of the defect. Specifically, the induced current decreases from $J_{\text{ind}} = 5.65 \times 10^7$ A/m² without defect to $J_{\text{ind}} = 4.58 \times 10^7$ A/m with defect. This decrease is explained by the presence of the defect, which leads to an increase in the current trajectory, thus resulting in a reduction of their intensity.

Between the first and second layers, when the coil is positioned at an angle of 0° for both layers, we observe a slight increase in the maximum induced currents, despite the absence of a defect. Indeed, the displacement of the sensor relative to the rivet head (and the rivet hole) leads to a slight increase in the current trajectory, resulting in a decrease in their intensity.

For the second layer, we notice that the intensity has decreased, with the
entire crown of induced currents displaying a yellow color, indicating a value lower than $5 \times 10^{-7}$ A/m².

Finally, for the last layer, the difference is minimal, of the order of $0.01 \times 10^{-7}$ A/m², which is consistent since the position at 90° of the coil relative to the defect places it far from it.

These results confirm the reliability of our model, allowing us to validate it and use it to obtain the desired images of a multi-element and multiplexed system.

4.2 EFFECT OF DEFECT PARAMETERS

In this section, we examine the impact of varying parameters that influence the impedance variation, such as frequency, width, and length, taking into account changes in the defect position, on the C-scan imaging.

4.2.1 Effect of frequency variation

We led the effect of three frequency variations Figures 4.5 and 6 clearly shows its effect on the sensor response.
4.2.1.1 Frequency: 30 kHz

Figure 4. Variation of the real part ($\Delta Z_r$) and the imaginary part ($\Delta Z_{imag}$) of the impedance for a frequency of 30 kHz; (a): $\Delta Z_r$, (b): $\Delta Z_{imag}$

Source: Authors.
4.2.1.2 Frequency: 40 kHz

Figure 5. Variation of the real part ($\Delta Z_r$) and the imaginary part ($\Delta Z_{imag}$) of the impedance for a frequency of 40 kHz; (a) $\Delta Z_r$, (b) $\Delta Z_{imag}$

Source: Authors.
4.2.1.3 Frequency: 50 kHz

According to Figures 4, 5, and 6, we observe that the variation of the real impedance ($\Delta Z_r$) is negative, with a maximum value of about 0.1 $\Omega$ at the middle of the defect, and it is zero all around the rivet. The value of $\Delta Z_r$ can reach -0.1 $\Omega$ for a frequency of 50 kHz, -0.9 $\Omega$ for a frequency of 40 kHz, and -0.8 $\Omega$ for a frequency of 30 kHz.

Regarding the variation of the imaginary impedance ($\Delta Z_{imag}$), it is zero around the rivet (in the absence of a defect). However, this variation is maximum at the middle of the defect, with values of about 0.32 $\Omega$ for a frequency of 50 kHz,
0.28 Ω for a frequency of 40 kHz, and 0.19 Ω for a frequency of 30 kHz. Thus, the obtained results confirm that the impedance variation is proportional to the frequency. This means that the higher the frequency of the electrical signal used in imaging, the more significant the measured impedance variations are. This relationship between frequency and impedance variation is consistent with the principles of electromagnetism and is essential for correctly interpreting the imaging data.

4.2.2 Effect of varying defect position

Figure (7) depicts the results of the variation in the real and imaginary parts of the impedance for three defect positions: defect1: 90°, defect2: 180°, and defect3: 300°.

Figure 7. Variation of the real and imaginary parts of the impedance for defect positions 90°, 180°, and 300°. (a): ΔZr, (b): Δzimag
The results obtained indicate that the peak of the variation in $\Delta Z_{\text{imag}}$ is uniform for all three defects, due to their identical geometric characteristics. This finding underscores the sensitivity of impedance measurement to geometry variations. Furthermore, the zero variation of $\Delta Z_{\text{imag}}$ in defect-free zones confirms the accuracy of the imaging method used.

Moreover, the maximization of $\Delta Z_{\text{imag}}$ at the center of defects, approximately 0.35 $\Omega$ for all three defects, offset by 90°, 180°, and 300°, highlights the technique’s ability to effectively detect anomalies. Additionally, the negative variation of $\Delta Z_r$, reaching approximately -0.01 $\Omega$ at the center of all three defects, suggests a decrease in the real resistance associated with the presence of defects. These results underscore the robustness of impedance imaging method for defect detection and characterization in materials.

4.2.3 Effect of varying defect width and position

The Figure (8) depict the results of the variation in the real and imaginary parts of the impedance for three defects with widths and positions: defect1: 0.2mm (at 90°), defect2: 0.5mm (at 180°), and defect3: 1.0mm (at 300°).
Figure 8. Variation of the real and imaginary parts of the impedance for defect widths and positions: 0.2mm (90°), 0.5mm (180°), and 1.0mm (300°); a) ΔZr, b) ΔZimag

The results demonstrate that the variation in ΔZimag is insignificant around the rivet, where no defects are present (Figure 8(a)). Furthermore, the peak of these variations correlates with the different defect widths, highlighting the sensitivity of the imaging method to detecting dimensional variations.

However, the real variation in impedance, ΔZr, exhibits a negative trend (Figure 8(b)) and becomes zero beyond the defects. Additionally, it is noteworthy that the trough of these variations varies according to the defect width variation, emphasizing the technique's ability to detect and characterize irregularities of different dimensions.
4.2.4 Effect of varying defect length and position

The Figure (9) depicts the results of the variation in the real and imaginary parts of the impedance for varying defect positions and lengths of the three defects: defect1: 7.5mm (90°), defect2: 10.0mm (180°), and defect3: 12.5mm (300°).

Figure 9. Variation of the real and imaginary parts of the impedance for defect positions and lengths: 7.5mm (90°), 10.0mm (180°), and 12.5mm (300°); a) ΔZr, b) ΔZimag

The results illustrated by Figure (9 (a) and (b)) conclusively demonstrate that the variation in Δzimag and Δzr is closely related to the position and length of the defect. This observation highlights the crucial importance of these factors in interpreting impedance imaging data. By understanding how the position and length of the defect influence impedance variations, it becomes possible to enhance the accuracy and sensitivity of imaging methods for defect detection and
characterization in materials. These results thus reinforce the relevance of impedance imaging as an effective technique for non-destructive inspection.

These findings confirm the relevance and precision of the eddy current imaging method for evaluating defects in materials, providing detailed information on their geometric and electrical properties.

5 CONCLUSION

The results of our study using multi-element eddy current imaging with multiplexed feeding by the finite element method (FEM) demonstrate the relevance and effectiveness of this technique for modernizing traditional non-destructive testing (NDT) methods by eddy currents (EC). This approach offers the possibility of conducting rapid inspections without sensor displacement, resulting in fewer disruptive elements on the detection signal, and with exceptional spatial resolution, thus opening up new perspectives for characterizing structural defects encountered in various materials. Furthermore, this solution can be adapted to variations in rivet diameter.

Moreover, our results were very satisfactory regarding defect detection and characterization. The detailed imaging representations obtained by eddy current sensors offer very acceptable clarity, allowing us to highlight the sensitivity of detection according to influential parameters such as frequency and geometric dimensions of defects. These results confirm the reliability and robustness of our imaging method for accurately identifying structural anomalies.

In conclusion, our research emphasizes the importance and potential of multi-element eddy current imaging with multiplexed feeding by the finite element method (FEM) in the field of defect characterization. This approach offers a promising alternative to conventional methods, providing significant advantages in terms of spatial resolution and detection sensitivity, comprehensive coverage around domed head rivets, and significant speed as it does not require sensor displacement.

For the continuation of this work, one could implement pulsed current feeding to detect defects located in deeper layers or use coils fed in differential mode to eliminate parasitic signals.
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