Numerical simulation and experimental studies of rotational eddy current detection of cracks around rivet holes

Simulação numérica e estudos experimentais da deteção de fissuras em torno de furos de rebites por correntes parasitas rotacionais

Simulación numérica y estudios experimentales de la detección por corrientes de Foucault rotacionales de grietas alrededor de orificios de remaches

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ABSTRACT  
Multi-layered aeronautical structures, such as fuselage panels and wings, are composed of several layers of materials such as metal and composites. These structures are prone to damage such as corrosion, cracks and delamination between layers, which can compromise their structural integrity. Eddy current sensors are an essential tool for the inspection and preventive maintenance of multi-layered aeronautical structures, contributing to the safety and reliability of these crucial components. Differential-mode eddy current sensors are particularly well-suited for the inspection of multi-layer aerospace structures around dished-head rivets. The differential measurement improves the detection and characterization of defects in these complex geometries, which are prone to fatigue, corrosion, and other types of damage. The advantages of differential mode are improved sensitivity to small defects, elimination of lift-off variations (distance between the sensor and the surface), reduced electromagnetic interference and detection of defects around rivets, which are critical and difficult to access areas. This work deals with a study of the rotational differential sensor signal according to geometrical parameters of fastener holes defect. It is carried out by an eddy current nondestructive testing system implemented under COMSOL Multiphysics. Indeed, despite its rapidity, the results have shown that the sensor is sensitive to the hole defects when the distances Sensor/Rivet and Lift-off are reduced. As predicted, the experimental results have shown the presence of unsuitable signals caused by the additional Lift-off and the distance Sensor/Rivet. As a solution, these tow parameters should be reduced and kept constant in order to get a better defect signal.


RESUMO  
As estruturas aeronáuticas multicamadas, como os painéis da fuselagem e as asas, são compostas por várias camadas de materiais como o metal e os compósitos. Estas estruturas são propensas a danos como a corrosão, fissuras e delaminação entre camadas, o que pode comprometer a sua integridade estrutural. Os sensores de correntes de Foucault são uma ferramenta essencial para a inspeção e manutenção preventiva de estruturas aeronáuticas com várias camadas, contribuindo para a segurança e fiabilidade destes componentes cruciais. Os sensores de correntes de Foucault de modo diferencial são particularmente adequados para a inspeção de estruturas aeroespaciais multicamadas em torno de rebites de cabeça chata. A medição diferencial melhora a deteção e caraterização de defeitos nestas geometrias complexas, que são propensas à fadiga, corrosão e outros tipos de danos. As vantagens do modo diferencial são a melhoria da sensibilidade a pequenos defeitos, a eliminação das
variações de lift-off (distância entre o sensor e a superfície), a redução da interferência electromagnética e a deteção de defeitos à volta de rebites, que são áreas críticas e de difícil acesso. Este trabalho trata do estudo do sinal do sensor diferencial de rotação em função dos parâmetros geométricos dos furos de fixação com defeito. Este estudo é efectuado através de um sistema de ensaios não destrutivos por correntes de Foucault implementado no COMSOL Multiphysics. De facto, apesar da sua rapidez, os resultados mostraram que o sensor é sensível aos defeitos dos furos quando as distâncias Sensor/Rivet e Lift-off são reduzidas. Como previsto, os resultados experimentais mostraram a presença de sinais inadequados causados pelo Lift-off adicional e a distância Sensor/Rivet. Como solução, estes parâmetros de reboque devem ser reduzidos e mantidos constantes para se obter um melhor sinal de defeito.


**RESUMEN**

Las estructuras aeronáuticas multicapa, como los paneles del fuselaje y las alas, se componen de varias capas de materiales como metal y materiales compuestos. Estas estructuras son propensas a sufrir daños como corrosión, grietas y delaminación entre capas, que pueden comprometer su integridad estructural. Los sensores de corrientes de Foucault son una herramienta esencial para la inspección y el mantenimiento preventivo de estructuras aeronáuticas multicapa, contribuyendo a la seguridad y fiabilidad de estos componentes cruciales. Los sensores de corrientes de Foucault de modo diferencial son especialmente adecuados para la inspección de estructuras aeronáuticas multicapa alrededor de remaches de cabeza abombada. La medición diferencial mejora la detección y caracterización de defectos en estas geometrías complejas, propensas a la fatiga, la corrosión y otros tipos de daños. Las ventajas del modo diferencial son la mejora de la sensibilidad a los defectos pequeños, la eliminación de las variaciones de despegue (distancia entre el sensor y la superficie), la reducción de las interferencias electromagnéticas y la detección de defectos alrededor de los remaches, que son zonas críticas y de difícil acceso. Este trabajo aborda el estudio de la señal diferencial rotacional del sensor en función de los parámetros geométricos del defecto en los orificios de los elementos de fijación. Se lleva a cabo mediante un sistema de ensayos no destructivos por correntes inducidas implementado bajo COMSOL Multiphysics. En efecto, a pesar de su rapidez, los resultados han mostrado que el sensor es sensible a los defectos del agujero cuando las distancias Sensor/Rivet y Lift-off son reducidas. Como se predijo, los resultados experimentales han mostrado la presencia de señales inadequadas causadas por el Lift-off adicional y la distancia Sensor/Rivet. Como solución, estos dos parámetros deberían reducirse y mantenerse constantes para obtener una mejor señal de defecto.

1 INTRODUCTION

In Eddy current (EC) method is considered as most applicable for in-service detection of fatigue subsurface cracks initiated in aircraft multilayer structures near the rivet holes (Abdou et al., 2019a, Valentyn, 2020). At the same time, the successful solution of this problem is obstructed by additional noise created by defect-free rivets, (Abdou et al., 2019b Yushi et al., 2006). Fastening holes are usually the subject of more careful consideration, as they are often locations of initiation and propagation of cracks due to load transfer and stress concentration. Currently the most advanced eddy current nondestructive testing (EC-NDT) techniques take into consideration the detection of defects occurring in one of the layers in the presence of rivets and fasteners. The used methods require a significant penetration in order to ensure the inspection of the lower plates. On the other hand, these methods must distinguish the useful signal from noises ones created by many factors such as vibrations, additional lift-off, edge effect and space between layers , (Abbassi et al., 2020, El-Kahina, 2021).

The usual method of inspecting flat head rivet lines has problems during the inspection of round head rivets, because the round head hinders the passage of the sensor with constant Lift-off. Moreover, even if the rivet head is flat, the sensor is unable to detect the defect and its orientation with a single scan. In fact, this can facilitate relatively the inversion procedure by optimization method allowing us to determine the defect location, shape and size, (Chady, 2021, Salama et al., 2021).

Then, the inspection by sliding probe can act as a complementary procedure. Therefore, our study consists to study, by numerical simulation under COMSOL Multiphysics, the sensor signal according to defect geometrical parameters such as length, width and depth. Besides that, the distance Sensor / Rivet is an important factor and must be investigated. After obtaining the signals of the rotational eddy current differential sensor operating on a riveted multilayer structure by a numerical simulation, we proceed to compare the experimental results with the theoretical ones in order to demonstrate the presence of noises signals accompanying the useful differential signal. Indeed, the designer must take into consideration these factors influencing the appearance of these noises signals in order to minimize their effects.
2 ROUND HEAD RIVET AND PROBLEMS OF SLIDING EC INSPECTION

The flathead rivet, like the roundhead one, is used on interior structures, (Bouchala et al., 2015). It is used where maximum strength is needed and where there isn’t sufficient clearance to use a roundhead rivet. It is seldom, if ever, used on external surfaces. The brazier head rivet has a head of large diameter, which makes it particularly adaptable for riveting thin sheet stock (skin). The brazier head rivet offers only slight resistance to the airflow, and because of this factor, it is frequently used for riveting skin on exterior surfaces, especially on aft sections of the fuselage and empennage. It is used for riveting thin sheets exposed to the slipstream. A modified brazier head rivet is also manufactured; it is simply a brazier head of reduced diameter.

Roundhead rivets are used in the interior of the aircraft, except where clearance is required for adjacent members. This rivet has a deep, rounded top surface. Its head is large enough to strengthen the sheet around the hole and, at the same time, offers a resistance to tension, (Figure 1).

![Figure 1. Roundhead and flathead rivets scanning principle.](source: The authors.)

One of the big challenges is to control the rivet lines to detect possible cracking phenomena which can be created in the bore and propagate given the great mechanical stresses exerted on this area, (Abdou et al., 2019a; Underhill et al., 2018). Currently, existing inspection methods have shown their effectiveness and ability to detect a defect in the early state. However, the usual method of inspecting flat head rivet lines has problems during the inspection of round head rivets because the latter hinders the passage of the sensor because of the overflow of its head; which causes an additional Lift-off, (Figure 2).
Additionally, even if the rivet head is flat, the sensor is unable to detect the defect and its orientation with a single scan. It is for this reason that our study will be focused on defect detection in the presence of the round head rivet with a rotary probe.

Interestingly, the use of rotational probe permits to detect simultaneously the crack and its orientation. In fact, this can facilitate the inversion procedure by optimization method allowing a full crack characterization.

3 THEORETICAL STUDY BY FEM SIMULATION

3.1 GEOMETRICAL AND ELECTRICAL CHARACTERISTICS OF THE STUDIED DEVICE

The configuration of the studied device consists of three Al layers assembled with a round head rivet. The differential sensor is made of two identical coils with reversed winding. In reality, the sensor rotates around the rivet head in order to inspect the multilayer hole. On other hand, the artificial crack has a parallelepiped shape defined by its length Ld, depth Pd and width Wd, (Figure 3)
The physical and geometric characteristics of the studied device are given on Table 1.

<table>
<thead>
<tr>
<th>Coils</th>
<th>Bore</th>
<th>Defect</th>
<th>Sheets</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius (mm)</td>
<td>7.32</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Inner radius (mm)</td>
<td>3.74</td>
<td>3.1</td>
<td>75</td>
<td>5</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>3.46</td>
<td>10</td>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>Number of turns</td>
<td>926</td>
<td>8.5</td>
<td>Layer 2 thickness (mm)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Layer 2 thickness (mm)</td>
<td>4</td>
</tr>
</tbody>
</table>

Source: Authors

3.2 GEOMETRICAL MESH OF THE PROPOSED MODEL

The first task to accomplish when performing a numerical simulation is to define the computational domain, followed by the creation of the mesh for the chosen domain. This step can be considered both the most important and the most delicate in this preliminary work. Several types of discretization elements (tetrahedral, hexahedral or prism) are proposed by COMSOL Multiphysics (Abdou et al., 2023). In our case, we have adopted for tetrahedral elements, (Figure 4 and Figure 5).

Figure 4. Mesh of all domains.

Source: Authors
4 RESULTS AND DISCUSSION

After having implemented our model under COMSOL Multiphysics, we proceed to the visualization of some electromagnetic quantities in different domains, Fig(6 a and b).

Figure 6 illustrates the density of the induced currents in the absence of a defect.

The cartography of the induced current density in sheets 1, 2 and 3 is given in Figure 7, 8 and 9.

Through the previous figures, we can notice that the amplitude of the induced currents amplitude is the highest in the first layer and the lowest in the third one. Otherwise, the induced currents are distorted by the presence of the defect. Hence, this interaction induces a change in the sensor impedance and indicates the presence of an anomaly.
4.1 EFFECT OF EXITING MAGNETIC FIELD FREQUENCY

In this section we show the effect of the exciting field frequency of the on the sensor sensitivity. The obtained results for three frequencies are obtained in the Figure 10.
Figure 10. Evolution of sensor resistance and reactance with the angular position for three frequencies.

According to Figure 10, we can say that the best results are obtained for high frequencies because the defect is located on the sheet surface.

Through the yielded results, we notice that; as the length increases, the change in resistance and reactance also increases. This is merely justified by the increase in the distorted induced current lines as defect length increases as shown in the figures above.
4.2 PROBE SIGNAL ACCORDING TO DEFECT PARAMETERS

4.2.1 Defect length

We present in Figure 11 eddy current signatures representing the variations in resistance and reactance.

Figure 12. Cartography of the induced current density for $L_d = 3\text{mm}$ and $L_d = 7.5\text{mm}$.
Through the yielded results, we notice that; as the length increases, the change in resistance and reactance also increases. This is merely justified by the increase in the distorted induced current lines as defect length increases as shown in the figures below, (Figure 12).

4.2.2 Defect width

Figure 13 depicts the sensor resistance and reactance according to their angular positions for Ld=9mm, Pd of 2mm and having different widths Wd.

As expected, as the crack opens, the induced currents will have more difficulty to flow through the affected area and the corresponding impedance variations will be greater as shown in Figure 14.
4.2.3 Defect depth

Figure 15 presents the sensor resistance and reactance according to their angular positions for Ld=9mm, Wd of 0.2mm and having different depths Pd.

As known theoretically, the induced currents occupy the closest part to the sensor; although the induced currents decrease when reducing the depth, the
sensor remains relatively sensitive to the depth. This is what justifies the difference between the obtained signals as shown in Figure 16.

Figure 16. Cartography of the currents induced for Pd = 2mm and Pd = 3mm different depths.

![Figure 16](image1)

Source: Authors

Figure 17 presents the sensor resistance and reactance according to their angular positions for different values of distance Sensor/Rivet ratio.

Figure 17. Evolution of sensor resistance and reactance according to their angular positions for different values of distance Sensor/Rivet ratio.

![Figure 17](image2)

Source: Authors

4.2.4 Detectability limit for small defects size

In this section we study the probe detectability limit according to defect length and width, Figures (18-19).
Figure 18. Sensor responses for different defect length.

Source: Authors

Figure 19. Sensor responses for different defect width.

Source: Authors
From the obtained results we can confirm that the defect length affect strongly the probe signal amplitude in comparison to defect width.

5 EXPERIMENTAL DEVICE

EC technique is known for its easiness, versatility, speediness, and contactless nature, (Javier et al., 2011; Paillard et al., 2008). Several developments have taken place in the recent years for applying this technique to riveted panels in aircraft structures. Sliding probes are developed for detection of fatigue cracks in the skins of the riveted panels. For detection of fatigue cracks around the rivet heads we propose a differential rotating probe in order to reduce Lift-off noises encountered while using sliding inspections methods. The experimental work bench is formed by electronic and mechanical components as shown below in Figure 20.

This experimental work bench assures principally three tasks:
• step 1. Detection by EC differential sensor connected to impedance analyzer Zscope;
• step 2. Data acquisition and visualization in PC via the installed WinEC™ software;
• step 3. The rotation of the sensor around the rivet is replaced by the rotation of the entire multilayer structure with rivet around the rivet; this rotation is...
ensured by an electric motor plus a mechanical link connecting to a control system. This solution aims to facilitate the study and avoid disruptive effects during the rotation of the sensor, such as the variation of the lift-off, the verticality of the probe as well as the non-concentricity of the path of the sensor with the rivet.

5.1 IMPEDANCE ANALYZER AND DATA ACQUISITION WITH WINEC™

The Z-Scope v62 includes an excitation signal generator and a multiplexed two receiver channels. The signal generator generates a sine wave up to 100 kHz to stimulate an external circuit. The receiver has two multiplexed differential channels. The synchronous detector permits to determine the real and the imaginary parts of the input signals (determine the signal amplitude and phase).

5.2 ELEMENTS OF A BASIC INSPECTION SYSTEM

Figure 21 presents a block diagram of analog eddy current equipment. It includes a single tone generator which energizes the test coil sensor. Phase, frequency and amplitude can be adjusted to optimum parameters for the test pieces. When a crack occurs, the coil impedance experiences a change. The defect signal modulates the tone from the oscillator. A quadrature amplitude demodulator extracts the defect signal caused by the impedance variation. The demodulator outputs are X-axis and Y-axis signals. Each component represents the real and imaginary parts of the impedance respectively. These signals can be filtered and analyzed, (Javier et al., 2011; Uchanin, V., 2021).

The voltage signals, which represent the impedance changes in the inspection coil, can be displayed on a XY plot.
5.3 EC DIFFERENTIAL PROBE

The classical differential probes consist of two coils that compare two adjacent parts of the inspected material. The detecting coils are wound in the opposite directions to one another in order to equalize the induced voltages originated by the excitation primary field as shown in Figure 22, (Javier et al., 2011).

The output voltage of the differential coil probe is zero when there is no crack. Differential coils have the advantage of being able to detect very small discontinuities and eliminate the external disruptions such as velocity, temperature and Lift-off change. Therefore, this sensor is more adapted to the detection of small cracks.
We recall that, the exact geometric parameters of the probe are unknowns. For this reason, we do only a qualitative comparison between experiment and simulated results.

5.4 RIVETED ALUMINUM MULTILAYERS

The plane cockle is made, in majority, of aluminum alloys formed by aluminum mixed respectively with copper and zinc. Aluminum is used in general because its volume density is very low. This characteristic presents an advantage in aeronautics. Indeed, the more the plane is light, the less fuel consumption will be. Aluminum is also very appreciated its good resistance for corrosion and malleable what makes the construction of different part easier, (Abdou et al. 2019a; Abdou et al. 2019b). The material to be inspected consists of three riveted Al sheets, in which the rivet head diameter is about 6mm, (Figure 23).

Figure 23. Three Al sheets assembled by around rivet head.

5.5 DIFFERENTIAL DEFECT SIGNAL AND THE CORRESPONDING NOISES

Principally, the aims of this work are to study the impact of certain parameters on the sensor sensitivity and the stability of the generated signals. The main studied parameter is the Lift-off distance between probes and rivet PR. Furthermore, the vibratory effect generated by the rotation device will be considered.
5.5.1 Distance between probe and rivet

After studying the effect of the defect parameters and Lift-off on the sensor signal, we accomplish this investigation by analyzing the effect of the distance between the rivet and the sensor (PR) for 1600 Hz and Lift-off of 0.2mm. The yielded results are given in the following figures; (Figure 25).

From the above graphical results, one can confirm that the additional distance between probe and rivet axis is also the origin of the noise signals, but for the same Lift-off, the noise amplitude is minimal when PR is minimal (PR=3mm) because the defect signal is the predominant. Moreover, as the sensor moves away from the defect and rivet, the defect signature amplitude decreases and conversely the noise signal amplitude increases. In fact, this behavior can be justified by the non-horizontality of the inspected multilayers material. This is conducting to an important additional Lift-off. According to several works, as
solution, a special dielectric guide an applied for flush head rivets and probe centering. In all cases, this centering is retained during the probe rotation. During the inspection, the EC probe was installed coaxially to the rivet head and rotated after the balance operation. Good centering of the rivet and EC probe is very essential to minimize the noise produced by changes of the distance to rivet edge during rotation.

5.5.2 Lift-off

When a test probe is displaced around the rivet head, its impedance change is a function not only of the concerned variables such as material conductivity, coating thickness, size of surface or subsurface discontinuities, etc., but also of the probe’s Lift-off or tilt variation, which causes noise signals that obscure the valuable signals. Consequently, it is essential to suppress the noise signals for accurate interpretation of the valuable signals in eddy current testing.

The following figures show the sensor resistance and reactance evolutions versus the Lift-off for PR = 1mm, (Figure 25).

As predicted, the best defect signature is obtained when the sensor is near the surface whereas, outside of 2 mm, the sensor becomes insensitive. The additional Lift-off is an important parameter that can be an origin of noises, but for small values such as 0.2mm, the noise amplitude is almost without effect for PR=2mm. This can be justified by the mean of the small corresponding additional Lift-off.
6 CONCLUSION

Eddy-current testing (ECT) methods are commonly used in the inspection of aircraft skin for the detection of subsurface cracks. However, detection of defects is challenging because the weak eddy-current signal crack is dominated by the
strong signal response from the fastener. In addition, fastener sites act as strong discontinuities through the entire depth of the multiple layer structure and can mask signals from smaller fatigue cracks. Irregular geometric factors such as mis-drilled holes, fastener skew, probe tilt, presence of adjacent structures and corrosion around the fastener sites can also produce responses that are often difficult to distinguish from crack responses. Also, many factors need to be considered to differentiate crack signals from non-crack signals in rotational eddy current such as Lift-off and PR, (Valentyn, 2020). After having implemented the system under COMSOL Multiphysics, we have studied the sensor signal according to depth geometrical parameters such as the length, width and depth. Certainly, the results have shown that the sensor is sensitive to the variation of its dimension and orientation. On the other hand, the sensor becomes more sensitive to these variations when the distance Sensor / Rivet and Lift-off are minimal. After that, we have implemented an experimental work bench in the aim to demonstrate the presence of unsuitable signals. Through this experimental study, we can analyze and comment on the qualitative and quantitative aspect of the obtained differential sensor signals when it moves around a rivet hole with an artificial crack:

- the best defect signature is obtained when the sensor is near the surface whereas, outside of 2 mm, the sensor becomes insensitive. the additional lift-off is an important parameter that can be the origin of noises, but for small values such as 0.2mm, the noise amplitude is almost without effect for PR=2mm. this can be justified by the mean of the small corresponding additional lift-off;

- additional distance between probe and rivet axis is also the origin of the noise signals, but for the same lift-off, the noise amplitude is minimal when PR is minimal (PR=3mm) because the defect signal is the predominant;

- furthermore, high frequencies allow better sensor sensitivity, because the defect is situated in the first layer. but, in actual aircraft configurations the frequency must be less than 1.6 kHz, (Janovec Michal, 2019) , Lysenko et al., 2023) . On the other hand, the unsuitable signals are created from vibration, additional lift-off and PR. As a solution, these parameters must be reduced and kept constant in order to get a better defect signal, (Bouchala et al., 2015; Zhiwei et al., 2011; Underhill et al., 2018).
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REFERENCES


