A Novel Approach For The Eddy Current Inspection Of The Aerospace Structures Based On The Signal Modeling And Signal Processing

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Abstract
In the article the approach for the damage detection of the aerospace structures will be presented. The classical approach take into the consideration the optimalization of the inspection parameters such as frequency, size of the probe and potential probe type. Due to the influence of substructural elements such as reinforcements, different types of damages and damages overlapping (such as bottom of the top layer corrosion and the top of the bottom layer corrosion in multilayer structures) the damage characterization may be difficult. The article presents approach for the inspection based on the description of the electromagnetic signal distribution in the inspected materials using the numerical models based on the ANSYS software. Then the signal interaction with the structure will be presented and in the future works correlated with the measurements based on the eddy current and appropriate signal processing techniques. As the final result authors will deliver the concept of the numerical based software for the signal parameters optimalization required for the efficient structure inspection performance.

Keywords: Eddy Current, Signal Modeling, Signal processing

1. Introduction

The use of eddy currents especially for the aerospace inspection structures is very often the only solution for the damage detection (such as fatigue cracks, corrosion) especially for the multilayer structures inspection. The example of such issue is the fatigue crack inspection in the skin and in the substructure. The inspection with the ultrasonic’s may require the acoustic coupling between the selected elements of the aircraft which is not always possible. The use of eddy currents for the inspection of the aluminium alloy is the compromise between the possibility of the damage detection as well as the physical limitation of this method (limited depth of penetration, difficulties in signal interpretation without specialized reference samples). The inspection of the shape complicated materials, multilayer structures, different types of damages is associated with the necessity of having the specialised reference samples. The main goal for using such samples is to understand the signal behaviour and the signal response from the damage, the structure geometry or material properties change (e.g. non conductive layers). The preparation of such reference samples is expensive and time consuming. Another issue is the necessity of the PoD (Probability of Damage detection) estimation which will not be delivered in that article. The article will deliver the idea of the signal modelling approach. The modelling will enable the understanding of the signal behaviour in different inspection scenarios (such as different materials geometry, different damages etc.).
1.1. The Eddy Current inspection

Eddy Currents (EC) are useful tool for inspection of aluminum alloys. Limitation of that technique is connected with the so called depth of penetration which is dependant on conductivity and frequency of excitation of eddy currents in material under the inspection. The formula which covers the standard depth of penetration $D_p$ [mm] can be expressed as follows [1]:

$$D_p = \frac{661}{\sqrt{\mu^* \delta^* \mu}}$$  (1)

Where:
- $\delta$ [% IACS] – electrical conductivity;
- $\mu$ – magnetic permeability.

In the example shown in the Figure 1 the crack of the spar in the helicopter main rotor blade is visible as the result of C-scan eddy current inspection. Thickness of spar in most of the location is equal 3.3 mm. Based on conductivity measurement calculated depth of penetration is equal to 3 mm (Equation 1).

![Figure 1. Crack in the spar of the helicopter main rotor blade](image)

Another issue which is important during the eddy currents inspection is its density. Density of currents $J_x$ decreases with increasing depth of penetration. Formula which explains that phenomena may be expressed as follows [1]:

$$J_x = J_0 e^{-\frac{x}{d}}$$  (2)

where:
- $J_0$ – density of currents on the surface [A/m$^2$];
- $x$ – distance from the surface ;
- $d$ – standard depth of penetration.

Such phenomena should be considered when the inspection goes deeper in the structure for finding crack locations. Because of huge inspection area some applications should be used to increase inspection speed with maintain of reliability. For that reason automated data collection with the use of eddy currents [1, 2,3, 4] may be used. Such inspection enables fast and reliable data collection and data storing. The use of the automated eddy currents inspection for the aircraft structure is not free of the uncertainties connected with e.g. low density of currents (especially for the deep structures inspection). Also the non conductive layers (such as erosion protective straps or heating pockets in the leading edge installations) decrease the possibility of the damage detection. Taking that into the consideration the...
necessity of the signal modeling and the correlation of the model with the measurements may
be necessary. Especially the distribution of the currents and the magnetic field in the material
will assist the built of the approach for the inspection.

2. Description of the electromagnetic modelling approach

The possibility of using the Finite Element Method (FEM) for analysis of electromagnetic
phenomena and the eddy currents calculations was investigated in the early eighties [5]. The
first works in this field were based on simple two-dimensional models. These models allow
to obtain maps of distribution of the electromagnetic field and current density [6]. In following
years scientists began to examine the distributions of the fields around defects [7,8]. There
were also the first attempts to determine the characteristics of the signal from the crack [9].

Current development of numerical methods and increasing computational power of
computers allowed to take on more complex issue such as the modelling of eddy currents
density distribution for the surface layers and coatings [10]. There has also been work devoted
to the analysis of the impedance probe and consequently the more accurate determination of
the characteristics of the eddy current diagram [11]. Currently, attempts are being made for
the 3D modelling of the electromagnetic field distribution around the cracks [12, 13].

In this article the parametric, 2D models of probe-sample relation were created. Simulations
were performed in ANSYS 12. Obtained models allow for examination of:
- various location of the probe relative to the sample,
- electromagnetic field distribution depending on the electrical properties of surface layer,
- electromagnetic field distribution around the damage (depending on location and
gometry of the damage),
- distribution of eddy currents density etc.

These models are the starting point for further, more complex simulations that allow
modelling of the most common damage of the aerospace surface such as bottom of the top
layer corrosion and the top of the bottom layer corrosion in multilayer structures etc. Next
step will contain possibility of numerical calculation of characteristics of the signal from the
damage and layers (such parameters as phase angle, lift-off curves etc.).

In modelling electromagnetic phenomena using ANSYS software one of two formulas of
calculation could be selected. The first one involves the use of scalar magnetic potential
formulation (\( \mathbf{T} - \mathbf{\Omega}_s \), electric vector potential - scalar magnetic potential; [14]). The second
one is based on magnetic vector potential formulation (\( \mathbf{A} \), \( \mathbf{V} - \mathbf{A} \); magnetic vector potential, electric scalar potential-magnetic vector potential; [15,16]).

The selected type of the finite elements and solutions (transient, harmonic etc.) determine
the method of calculation. In this study calculations were based on magnetic vector potential
formulation (MVP). To better understand the course of calculations, the laws describing
electromagnetic phenomena (Maxwell’s equations) should be recalled. In this case the
occurrence of the displacement and convection currents were skipped [17,18]. That leaves
three equations presented below:

\[
\nabla \times \{E\} = -\frac{\partial B}{\partial t} \quad \text{Faraday's law} \quad (3)
\]

\[
\nabla \times \{H\} = \{J_s\} + \{J_e\} \quad \text{Ampere's Law} \quad (4)
\]

\[
\nabla \cdot \{B\} = 0 \quad \text{Gauss's law for magnetism} \quad (5)
\]

where: \( B \) – magnetic flux density, \( [T] \), \( E \) - electric field intensity \( [V/m] \), \( H \) - magnetic field
intensity \( [A/m] \), \( J_t \) – total current density \( [A/m^2] \), \( J_s \) source current density \( J_e \) eddy current
density), \( t \) – time, \( [s] \), \( \nabla \cdot \) divergence operator \( [1/m] \), \( \nabla \times \) - curl operator \( [1/m] \).
As we could see the divergence of B is always equal to zero (5). This means that field B could be introduced as a rotation of another field (6):

\[
\{ B \} = \text{rot} A = \nabla \times \{ A \} = \quad (6)
\]

where: \( A \) – magnetic vector potential [Wb/m]. In this case field \( A \) – magnetic vector potential.

With additional boundary condition described by equation (7) and scalar electric potential given by equation (8) the two Maxwell equations (3) and (5) are following:

\[
c^2 \nabla \cdot A + \frac{\partial V}{\partial t} = 0 \quad (7)
\]

\[
\{ E \} = -\left\{ \frac{\partial A}{\partial t} \right\} - \nabla \cdot V \quad (8)
\]

where: \( V \) – electric scalar potential, [V].

Then, taking into account the basic law (9) and currents density divergence the Ampere's Law (4) is also satisfied:

\[
\{ H \} = \frac{1}{\mu} \{ B \} \quad (9)
\]

where: \( \mu \) – magnetic permeability [H/m].

Then, the first result of the calculations is the distribution of magnetic flux density \( B \) (6). On this basis the magnetic field intensity \( H \) (9) is calculated. The density of induced eddy currents is determined by (10):

\[
\{ J_e \} = -\gamma \left\{ \frac{\partial A}{\partial t} \right\} \quad (10)
\]

where \( \gamma \) – electrical conductivity [S/m].

2.1 Examples of the eddy currents distribution

Below are some examples of the eddy currents distribution, depending on different variables. At first, simulation of eddy current testing measurement was developed (Figure.2). Distribution of eddy currents density for the different probe positions (step 1-6) relative to a sample containing damage (2 mm depth, 0.9 mm width) was obtained. The change in electromagnetic field around defect, during EC surface scan can be observed. That gives us tool to calculate eddy currents characteristics (future study).
Model correlation depends on change in frequency (1 - 100 kHz) which was also obtained. In Figure.3 change in depth of eddy currents penetration could be observed. The depth of penetration decreases with increasing frequency (as described by equation 1).

In the next case the distribution of eddy currents in sample with conductive layer (thickness 1mm) and damage (1mm depth, 0.9 mm width) below this layer were obtained. The maps of field distribution are shown in Figure.4 and Figure.5 (vector plot). The damage is clearly visible for frequency 1kHz.
The last case shows the distribution of eddy currents in sample with non-conductive layer (thickness 1mm) and damage (1 mm depth, 0.9 mm width) below this layer. The maps of field distribution are shown in Figure.6 and Figure.7 (vector plot). The damage is clearly visible for frequencies 1 kHz and 10 kHz.
Considered models could be used in damage detection of the aerospace structures (example: the case of bottom of the top layer corrosion and the top of the bottom layer corrosion in multilayer structures).

3. Example results of the inspection

One of the inspection issues is the determination of the corrosion (e.g. pitting corrosion) in the skin of the aircraft. In the article introduction data about the modelling of the field and the selection of the parameters were delivered. That information will be required for the proper parameters selection for the inspection of the aircraft elements such as:

- Frequency of the inspection;
- Probe type and size of the diameter.

In the figure 8 the results of the inspection of the specimen presented on the left are delivered. The visible colours presented in the C-scan are associated with the respond of the signal in the impedance plane. Impedance plane where the signal is analysed may be presented with the use of vector components. Such components describe the amplitude of the signal (the intensity of the damage) as well as the signal phase (which may refer to the depth of the damage location). The equation which describes such components may be described as [19]:

\[
Z = \sqrt{R^2 + (X_L - X_C)^2} \quad [\Omega]
\]

where:
- \(Z\) – electrical impedance;
• $X_L = 2\pi fL \ [\Omega] – \text{inductive reactance}$;
• $X_C = 1/(2\pi fC) \ [\Omega] – \text{capacitive reactance}$;

The measurement of the signal phase may be based on the following equation:

$$Tan \Theta^* = \frac{(X_C - X_L)}{R} \quad (12)$$

The use of flaw detectors enables the determination of the phase angle and the simple signal operation. But the inspection of the larger areas enforces the use of automated systems. For such systems the image visualization as presented in the Figure.8 is applied. For such visualization the image processing may be enabled which makes possible to apply more sophisticated signal processing methods for the:

- determination of the damage size,
- determination of the depth of the signal location;
- influence of the non conductive layer determination etc.

For the presented results in the Figure.8 the determination of the damage size and the depth differences was possible. Another issue is the determination of the corrosion location (top of the bottom skin or the bottom of top skin). Additionally the presence of the air gaps may interfere with the results of the inspection. Another approach for the data assessment is the application of the image processing techniques for damage evaluation and comparison. Such approach may help in determination in damage location and damage type.

The digital image is a two-dimensional discrete signal. It means that for the processing purposes, such signals can be presented as brightness function of two independent variables (an array) of the $M \times N$ size. As the example, the data from the monochrome digital image on the $n$ bits resolution per pixel may be presented [20] as follow:

$$f(x, y) = \begin{bmatrix}
  f(0,0) & f(0,1) & \cdots & f(0,N-1) \\
  f(1,0) & f(1,1) & \cdots & f(1,N-1) \\
  \vdots & \vdots & \ddots & \vdots \\
  f(M-1,0) & f(M-1,1) & \cdots & f(M-1,N-1)
\end{bmatrix} \quad (13)$$

where:

$f(x,y) \in C$;

$0 \leq f(x,y) \leq L-1$ and $L = 2^n$.

For such image presentation each pixel of the digital data corresponds to an array element. For the damage processing purposes operations on the Region of Interest (RoI) were performed. RoI may be defined as the locations of the damages on the inspection image. Depending on the number of damages located on the scan image, automated extraction of the RoI’s (based on indication of the damage locations) for the sub-arrays has been performed. Also detailed RoI analysis based on the array operations of the selected area is possible. Sub-arrays are created in accordance with the following procedure [20]:

$$A[x_i, y_j];$$

$$RoI[m,n] = C[M - x_i, N - y_j]; \quad (14)$$

where:

$C \ [M,N] – \text{scan image}$;

$A[x_i, y_j] – \text{array with damages coordinates}$;

$RoI[m,n] – \text{subarray of the C[M,N] array which includes RoI with i-rows and j-columns and where: } i = M-x_i, j = N-y_i$. 
In the figure 9 the results of the signal processing (such as: damage size determination, amplitude of the signal visualization) are presented. The results are the pitting corrosion of different intensity modelled in the aluminium alloy plate. These methods enable automated determination of the selected parameters required for the damage description (such as damage size, damage location, damage shape etc.).

Further works will be focused on the development of the modelling methods and the correlation with the measurements.

4. Conclusions

The article presents the approach for the damage detection in the aircraft structure with the use of mathematical modelling of the electromagnetic signal propagating in the structures. At first the authors were focused on the delivery of the information about the approach to the work. Since the efficient aircraft inspection may require to have the related number of specimens for the signal calibration the use of modelling may be a solution helping in the preparation of the inspection. The article presents the approach for the modelling methods which were elaborated by the main author of the article. These methods will be used for the creation of the models with various scenario of the damages which may occur in the aircraft structure mostly 2017 and 7075 aluminium alloys. For the description of the inspection approach the information about corrosion detection (especially in the multilayer structures) was delivered. Moreover, the signal processing of the eddy current signals was delivered. Further works of the authors will be focused on the elaboration of the software for the modelling of the signal for the required inspection needs. For that purpose the different damages scenarios, materials and the structures will be considered.

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