Modeling and simulation of defects detection in conductive multi-layered pieces by the eddy current technique

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Abstract. It has been shown that the eddy current method is one of the most effective techniques for the detection and characterization of surface and near-surface defects in conductive mediums especially in aluminum alloy. It is one of the most applied methods in industries which require a maximum of reliability and security (aerospace, aeronautics, nuclear, Etc).

In this study, a code to solve electromagnetic problems by employing the finite element method is developed. The suggested model can simulate the probe response to the presence of a defect hidden in a multi-layered structure or a riveted structure on aluminum alloy. The developed code is based on the discretization in three dimensions of the Maxwell's equations in harmonic mode by the finite element method based on the combined potential formulations. That will enable us to interpret the results, to present them in graphical form and to carry out simulations for various applications

Keyword: Non destructive testing, eddy current, finite element method, aluminum parts, numerical simulations, inversing problem.

1. Introduction

The insurance of operation of the aircraft in the event of suspect or presence of damage requires the determination of critical elements in its structure. These elements should be identified during the design of the aircraft, and also during in-service exploitation.

Riveted joints have been frequently used in aeronautics for a long time. They present an important subject for much recent researches. This is due to the fact that very often rivet holes are places where fatigue cracks, corrosion and other defects occur; the last are crucial for the fatigue life and safe operation requirements [1, 2]. These defects are critical problems of in-service aircraft structures which lead to a degradation of structure integrity and fatigue resistance and directly affect the airworthiness of an aircraft and even result in loss of fuselage skin sections [3].

Eddy current testing can be used for a variety of applications such as detection of cracks (discontinuities), measurement of metal thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness and the measurement of electrical conductivity and magnetic permeability. Eddy current technique is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known. In aeronautics for example, eddy current testing is used for over 50% of all applications for the detection of hidden defects in fuselage skins and multi-layers. [4]- [6].

In this work, we measured the magnetic signal due to the defects inside a thick aluminum plate and compared our results with the theoretical calculation. From calculated parameters, we deduce the real and imaginary components of the impedance which makes possible to determine the characteristic parameters of a crack in various metallic parts. With this method, we try to detect crack defects in the bottom layer of lap-joined aluminum plates.
2. Modeling
Cracks and corrosion frequently develop in the fuselage, often in hidden layers close to rivets (figure 1).

Figure 1. Internal view of crack development in riveted structure (longeron).

Modeling and simulations of eddy current technique using the numerical models of the finite element method (FEM) in order to found codes able to solve Maxwell’s equations have been developed in different papers in the latest years [7]-[9].

In this paper, the related direct problem consisting of modeling the impedance coil response over a multilayered structure used in eddy current testing is treated. Following the approach developed in [10, 11] for planar multilayer medium with constant electrical and magnetic properties, the numerical formulation of FEM is well established and the two main steps for establishing the model are determining the vector potential $A$ and then calculating the coil impedance $Z$.

For a homogeneous extended conductor placed in a time-varying external magnetic field, with a frequency that is low enough that displacement currents and finite propagation velocity effects can be neglected. Using the formulation in potentials based on the introducing of two potentials, the magnetic vector potential $A$ and the electric scalar potential $V$, the eddy current problem in terms of the magnetic vector potential can be described mathematically by the following equation (more information and details have been shown in [4, 5, 7, 9]):

$$ \nabla^2 A + K^2 A = -\mu J $$

(1)

where $A$ represents the magnetic vector potential, $\mu$ is the magnetic permeability of the tested domain, $J$ is the excitation current density, $K^2 = -j\omega\mu(\sigma+j\omega\varepsilon)$, $\omega$ is the angular frequency of the excitation current, $\sigma$ is the electrical conductivity and $\varepsilon$ is the dielectric constant.

Based on the Galerkin’s method where irregular meshes of tetrahedral elements were used, the finite element formulation of (1) can be developed.

After some usual mathematical manipulations, the approximation of nodal values results in equations and elemental contributions of the solution can be calculated and summed into a global system of equations:

$$ [K] \{A\} = \{Q\} $$

(2)

where $[K]$ is the $N\times N$ banded symmetric complex global matrix ($N$ is the total number of nodes), and $\{Q\}$ and $\{A\}$ are respectively the $N\times 1$ complex source matrix and the $N\times 1$ complex vector of unknowns.

Khalestki algorithm is applied to resolve this system of equations, taking advantage of the symmetry and bandwidth, to solve for $A$ at the nodes of the finite element mesh.

From the $A$ values, other quantities can be calculated such as flux densities. The dissipated energy $P$ in the conductor and stored energy $W$ in the whole solution domain can be calculated [4, 5, 7, 9].

The change in resistance $R$ is associated with dissipated energy $P$ and the change in inductance $L$ is associated with the stored energy $W$.

The measurement model for coil impedance can be expressed in terms of changes in resistance and inductance in its complex form such as:

$$ Z = R + j\omega L $$

(3)
3. Application and results

In the paper, we want to show how the developed program could be used in simulations of the non-destructive testing of aeronautical pieces.

For the simplicity we consider only an axisymmetric problem and the algorithm will be applied to some plated aluminum samples.

![Figure 2. Test sample of second layer cracks.](image)

The test sample shown in figure 2 is made of two aluminum layers. Each layer is 200 mm x 200 mm and 2.5 mm thick, the electrical conductivity is 17 MS/m and the relative permeability is 1.

A rectangular shaped defect is located on the surface of the second layer with length (L) of 10 mm, width (w) of 0.2 mm and depth (d) of 1 mm.

The coil properties and test parameters are inner radius (Ri) of 6 mm, outer radius (Ro) of 12 mm, probe length (PL) of 12 mm, number of turns (N) of 900, lift-off (l) of 0.1 mm, skin depth of 6 mm and frequency of 500 Hz.

In order to detect cracks with a known orientation in the sample (scan was carried out along the defect length that correspond to the axis Ox), it is convenient if the current can be injected (or induced) in two orthogonal directions. For a sample with rectangular geometry (see figure 1), it is easier to inject a uniform current longitudinally than transversely. In this simulation, the results obtained when a transverse current is induced in the test sample by a probe, carrying a 50 mA 500 Hz current that was located below the test sample are discussed.

Figure 3 shows the relationship of the impedance change and the positions of the probe. It can be seen that the impedance curve has a peak when defect is present, and the distance between the peak-start and peak-end points is just the approximate length of the defect.

The maximum amplitude appears as the probe is positioned over the centre of the defect.

The developed code can carry out to study the influence of certain parameters. In this part, simulation work is carried out for defects, the test parameters are fixed (the same parameters quoted in previous paragraph) and the frequency is modified, using the developed program.

![Figure 3. Impedance versus probe position.](image) ![Figure 4. Defects detection of various frequencies.](image)
For cracks located deeper in the conductor, the optimum excitation frequency moves towards lower values (figure 4).

Factors such as the type of material, surface finish and condition of the material, the design of the probe, and many other factors can affect the accuracy of the inspection.

4. Conclusion

Eddy current techniques are widely used for detection of surface cracks in metallic structures. These techniques have limited success in the detection of deep and subsurface defects that require low frequency eddy currents.

In this work, we calculated and measured the normal component of the magnetic fields due to a uniform current injected into a two aluminum plates assembled together that contains defects. From this parameter, we deduce the real (resistance) and imaginary (inductance) components of the impedance which makes possible to determine the characteristic parameters of a crack in various metallic parts.

Obtained results show that this method is adapted to selected problem. And from simulation, we see that the parameters of defects can be characterized according to the impedance amplitude.

Furthermore, the results also show that feasible to use the developed code to provide the forward solutions for the eddy current inversion problem which is sizing of inspected defects by scanning multi-layered structures, and to carry out simulations for other geometries of materials with different proprieties in order to study the limits of the chosen technique.

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