Numerical simulation for cracks detection using the finite elements method

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ABSTRACT
The means of detection must ensure controls either during initial construction, or at the time of exploitation of all parts.

The Non destructive testing (NDT) gathers the most widespread methods for detecting defects of a part or review the integrity of a structure.

In the areas of advanced industry (aeronautics, aerospace, nuclear …), assessing the damage of materials is a key point to control durability and reliability of parts and materials in service.

In this context, it is necessary to quantify the damage and identify the different mechanisms responsible for the progress of this damage. It is therefore essential to characterize materials and identify the most sensitive indicators attached to damage to prevent their destruction and use them optimally.

In this work, simulation by finite elements method is realized with aim to calculate the electromagnetic energy of interaction: probe and piece (with/without defect).

From calculated energy, we deduce the real and imaginary components of the impedance which enables to determine the characteristic parameters of a crack in various metallic parts.

Keywords: Eddy current, Non-destructive testing (NDT), Cracks, Finite Element Method

1. INTRODUCTION

The Non-destructive testing (NDT) falls under the general concept of quality assurance, it plays a key role in all the applications claiming a maximum of safety and reliability (aeronautics, nuclear, automobile…).

The need to control complex parts leads to design increasingly advanced appropriate methods.

The next aircraft generation has to comply with the forthcoming more stringent regulations. Furthermore the general aviation standard with respect to the two-bay-crack criterion should be reached without special design precautions, such as crack stoppers, and without disadvantages in weight [1].

Eddy current testing can be used for a variety of applications such as the 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 inspection is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known [2].

Surface cracks sizes have been estimated based on a combine between two techniques (numerical one: dipole model of a crack and experimental one: Hall element measurements in [3]). The magnetic flux leakage technique has been utilized to characterize the defect by solving an inverse problem based on a space mapping methodology [4].

Eddy current testing can be used such as perfect tool to characterize defects in materials [5]. However, the sensitivity of the characterization process is highly dependent on the probe choice and the operation frequency [6].

Defects such as cracks are detected when they disrupt the path of eddy currents and weaken their strength.

Factors such as the type of material, the surface finish and condition of the material, the design of the probe, and many other factors can affect the sensitivity of the inspection [7].

The evaluation of NDT modeling tools is the principal goal of this study. Main concerns of the aeronautic industry and the potential contribution of modeling are discussed and illustrated.

The modeling approach can be divided into analytical and numerical models with the ability to solve Maxwell‘s equations.

In this context, various techniques for modeling NDT problems are already available. In this study, an approach based on finite elements method is chosen.

We therefore have developed a simple model for calculating the optimum excitation frequencies for cracks in different depths of tested parts.

By 3D- finite elements method (FEM) simulations we can get values of the current density at both sides of the crack and compared there with calculated values for the case with no crack.

2. CRACKS IN AERONAUTICAL STRUCTURE

The apparition of defect on aircraft parts is a formidable challenge and it calls for stringent quality control measures at various stages of its processing.

Cracks in aeronautical parts can occur due to a variety of mechanisms, such as stress-corrosion cracking, fatigue cracks, or inter-granular attack in tubes. They can initiate from the surface of part or from the interior of part, and can be axial, circumferential, or branching. They occur most frequently at tube, sheet transition, support, and U-bend regions.

The crack designates an anomaly (a defect) which occurs as a fracture whose appearance at the microscopic level, it’s due to a rupture on compression with an important deformation of cells accompanied by numerous transverse cracks in the walls [1,8,9]. The result is the appearance of irregular wrinkles on the surface of the material in the perpendicular direction to the fibers; it creates in most cases a very low tensile strength of longitudinal traction.

The compression cracks indicate a final break of the material caused by excessive load or shock in the fibers of the wall.

It is important to mention that the morphological analysis of the ruptures reveals many modes of ruin, which are functions of the stress type, of the presence of defects or plans of weakness of material.

A crack is not characterized by cracking of the material but by deformation comparable with pleating.

It is particularly mentioned that the development of the ruin does not depend only on the zone of principal weakness but also on the history of the loads applied to the part. (The way these loads have been applied is a major factor).

3. BASIC PRINCIPLES OF EDDY CURRENT

Eddy current is used in aircraft maintenance to inspect jet engine turbine shafts and vanes, wing skins, wheels, bolt holes, and spark plug bores for cracks, heat or frame damage. Eddy current may also be used in repair of aluminum aircraft damaged by fire or excessive heat. Different meter readings will be seen when the same metal is in different hardness states. Readings in the affected area are compared with identical materials in known unaffected areas for comparison. A difference in readings indicates a difference in the hardness state of the affected area. In aircraft manufacturing plants, eddy current is used to inspect castings, stampings, machine parts, forgings, and extrusions [10].

Eddy current testing works on the principles of electromagnetic induction. In eddy current technique, a coil is excited with sinusoidal alternating current (frequency range 50 Hz - 5 MHz) to induce eddy currents in an electrically conducting material. The change in coil impedance Z that arises due to distortion of eddy currents at regions of discontinuities and associated magnetic flux linkages is measured.

Eddy current test phenomenon is controlled by the *skin effect*, according to which the depth of penetration, depends on frequency and material properties [12, 13].

For a rough estimation of the optimum excitation frequency for a given test object, the well known expression for the skin penetration depth δ can be used as

$$\delta = \sqrt{2/\sigma\omega\mu} \tag{1}$$

Where ω is the excitation frequency, σ is the conductivity and μ is permeability of the investigated material.

Due to the skin effect, the detection and characterization of surface defects is more reliable as compared to buried or sub-surface defects. Popular industrial applications of eddy current testing include defect detection, material property measurement, alloy sorting, and material as well as coating thickness measurements. It is also used for proximity sensing, level measurements, and metal particles in non-conducting media.

Here, the wave propagation in a conducting medium is calculated by solving Maxwell's equations, assuming a planar incident electromagnetic wave and a conductor of semi-infinite extent. We can write the time independent solution for the amplitude of eddy current density in the form:

$$j = j_0\, e^{-\alpha Z} \tag{2}$$

Where α alpha is the inverse of the skin depth δ, j_0 is the current density on the surface of the conductor and z is the depth of penetration.

For calculating an optimum excitation frequency one has to consider two facts:

First, the eddy current density is damped while penetrating into the conductor (penetration effect). Here the frequency dependence of the penetration depth implies that for deep lying cracks low frequencies must be used for obtaining a sufficient current density in the vicinity of the crack. Secondly, due to the induction law the induced current density at the surface jc0 is diminished when using lower frequencies. Therefore, in total, there is a certain excitation frequency which results in a maximum response field from the crack.

4. PROBLEM MODELING

Simulation and modeling appear such as quick efficient tools as they could enable to share information that concerns the defect between all interested.

Modeling and simulation of eddy currents testing provide a good basis for allowing an early evaluation of part inspection. Emerging tools can take reliably into account the geometry, material properties and representative defects. They could also give an approximate value of the defect size that could be detected.

Cracks and corrosion frequently develop in the fuselage, often in hidden layers close to rivets (Fig 1).

Various techniques for modeling NDT by eddy current problems are already available. In this study, an approach based on finite elements method is chosen [11,12,13,15].

The equations governing the general time varying fields in section include magnetic and conducting materials can be derived from the Maxwell equations:

$$\nabla \times B = \mu\, (J + \delta D / \delta t) \text{ (Ampere-Maxwell theorem)} \quad (3)$$

$$\nabla \times E = - \delta B / \delta t \text{ (Faraday's law)} \quad (4)$$

$$\nabla .\, B = 0 \text{ (law of conservation of magnetic flux)} \quad (5)$$

$$\nabla .\, E = \rho / \varepsilon \text{ (Gauss theorem)} \quad (6)$$

Where: μ ε are respectively the permeability and permittivity of the medium, _ represents the volume density of electric charges (C/m^3), E is the electric field (V / m), B is the magnetic induction (Wb/m^2 or T), j is the conduction current density (A/m^2), D is the electric induction (C/m^2).

The constitutive relations are given in the following forms:

$$B = \mu\, H \quad (7)$$

$$D = \varepsilon\, E \quad (8)$$

$$j = \sigma\, E. \quad (9)$$

H is the magnetic field (A / m), σ the conductivity of the medium (S / m).

The eddy current problem can be described mathematically by the following equation in terms of the magnetic vector potential [11,12,13]:

$$\nabla^2 A + K^2 = -\mu J \quad (10)$$

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

The *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 [14-15].

From A, other quantities can be calculated such as flux densities and coil impedances.

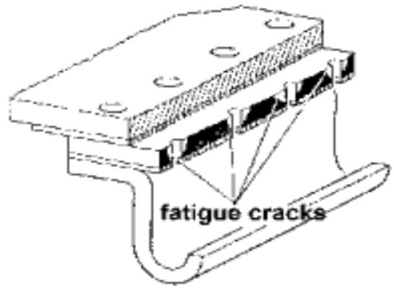

Figure 1: Example of controlled structure in aeronautical industry

5. DESCRIPTION OF PROGRAM

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

For the simplicity we consider only an axisymmetric problem that consists of piece made of aeronautical materials.

Developed data-processing is consisted of three parts:

Input data interface: which is a multiple interface contains a various parts for laying out the geometry of the problem and for defining material properties and boundary conditions.

Mesh generation– generates automatically a various types of meshes.

Resolution of problem – where a matrix construction is performed and a global system of equations is solved using the method of *Khalestki*. Each solution takes a set of data files that describe problem and solves the relevant Maxwell's equations to obtain values for the desired field throughout the solution domain.

Field solutions can be displayed in the form of contour and density plots.

For every problem the user has to define an adequate number of boundary conditions to guarantee the unique solution.

Boundary conditions for a developed data-processing are of three types:

- *Dirichlet* - the value of vector magnetic potential A or scalar electric V is explicitly defined on the boundary.
- *Neumann* (natural) - the normal derivative of potential along the boundary is specified.
- *Cauchy* (mixed) - defines a relationship between the value of potential and its normal derivative at the boundary.

The program enables also to view distributions of several variables which presents the distribution of a magnetic flux density on the inner side of the piece for two cases: without crack and with the surface crack. However these tools although can be easy applied to show only a qualitative presence of the crack in investigated region.

Usually in NDT problems the results of simulations are presented in a form of complex impedance trajectories (butterfly plots).

6. SIMULATIONS AND DISCUSSION

The algorithm was applied to some plated (or riveted) aluminum samples, the method of eddy current requires a reference like standard (the state or sought discontinuity must be defined).

Standard with the external (or internal) cracks of various depths can be used [7-9]. The material specifications of the standard must be similar to the material specifications of the inspected part. The widths of the cracks are 0.2 millimeter; the depths of the cracks are 0.2 millimeter to 2 millimeter.

A representation in two dimensions crack was used (see Figure 1), with length of 10mm and depth of 1mm, material used is aluminum 2024 with conductivity 17 MS/m, and permeability 1, used samples are simple layer part (or multi-layers part of same material) of 60mm*60mm with 2.5mm depth.

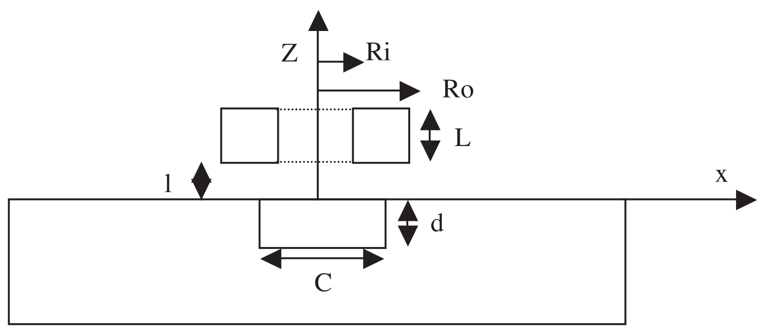

Figure 2: Studied configuration.

The parameters for this test are listed in Table 1.

Table 1: Parameters of Studied case

The coil	
Inner radius (Ri)	6. mm
Outer radius (Ro)	9. mm
Length (L)	6. mm
Number of turns (N)	900
Lift-off (l)	1. mm
The test plate	
Thickness	2.5 mm
Conductivity	17 MS/m
Permeability	1
Crack is in the first lower plate	
Length (c)	10. mm
Depth (d)	1. mm
Width (w)	0.2. mm
Other parameters	
Frequency	7000 Hz
Skin depth at 7000 Hz	1.4mm

A scan was carried out along the defect length (along the axis Ox). The figure (Fig. 3) presents simulations mention the variation of the resistive part (real value) and the reactive part (imaginary value) for the selected test.

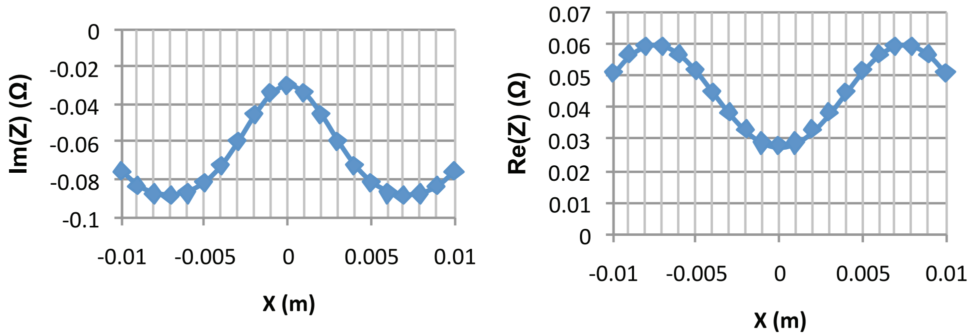

Figure 3: real and imaginary components of the impedance variation.

The developed code can carry out to study the influence of certain parameters.

In the example presented in the figure Fig4, the parameters of test are fixed (the same parameters quoted in table 1), and the frequency is modified.

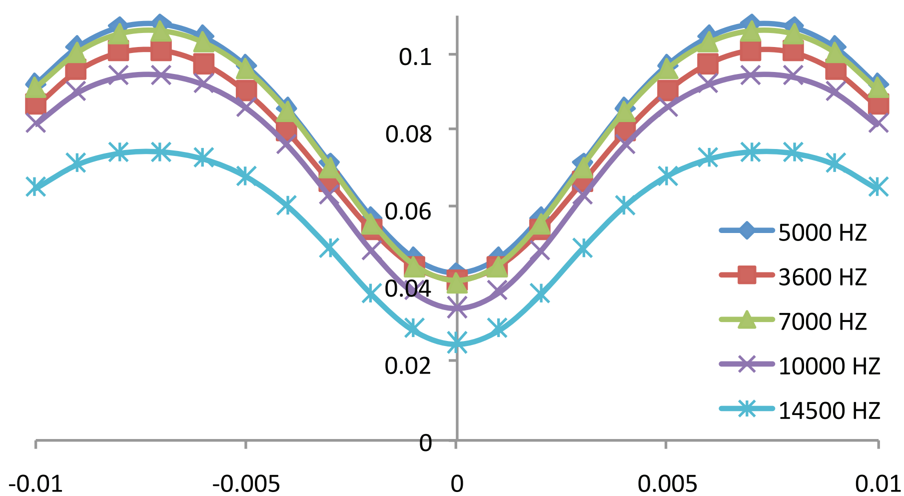

Figure 4: Defects detection of various frequencies

The distorted current has in a first order approximation the shape of a circular current flowing in the x-y plane. The current flowing in z-direction above and below the crack does not contribute, because it causes only a negligible change in the z-component of the magnetic field.

For cracks located deeper in the conductor, the optimum excitation frequency moves towards lower values.

In reality, aircraft parts can consist of several stacked layers of material, connected by rivets or bolts. To avoid corrosion, the layers are often protected by a special coating, so that there is no electrical connection between the layers. If there is a crack for example in the middle layer, no current will thus flow above or below the defect because of the insulating coating between the layers. There is only the possibility for the current to flow around the crack in the x-y plane, which results in a higher response from the crack as compared to the case of a massive (non-layered) sample.

7. CONCLUSION

Aircraft, being exposed to strong forces such as moisture and changing temperatures, have to be checked regularly for cracks and corrosion. Non destructive testing of aging aircraft structures is essentially used for flight safety and for maintenance costs reduction. Of the many NDT methods being used in aircraft maintenance, eddy-current testing is a well established technique, especially for layered structures.

Eddy current is a NDT method that uses electricity and magnetism or electromagnetic induction to create a magnetic field in the article under inspection.

Routine eddy current inspection is carried out on aircraft under carriage wheel hubs for cracks also used to detect cracks in different tubes, tubular components of aircraft and engine.

Defects such as cracks are detected when they disrupt the path of eddy currents and weaken their strength.

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

In this work, simulation by finite elements method is realized with aim to calculate the electromagnetic energy of interaction: probe and piece (or fissured part).

From calculated energy, we deduce the real and imaginary components from the impedance of the sensor, which makes it possible to determine the characteristic parameters of a crack in various metallic parts.

Obtained results show that the applicable method is adequate and has a good adaptation to desired problems. Indeed, test parameters can be changed and entered automatically and responses versus different frequencies can be obtained.

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