Quantifying Hidden Defect in Multi-layered Structures by Using Eddy Current System Combined with a Scanner

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Abstract. The eddy current testing forward model of scanning inspection of multi-layered structures is introduced and simulation work is carried out to reveal the interaction between the scanning coil and defects with different geometric properties. A multi-frequency ECT experimental instrument combined with a scanner is established and scanning inspections are performed to detect the artificial etched flaws with different geometric parameters in the multi-layered structures. The predicted signals by the forward model are compared with the measured signals and the defects are characterized.

1. Introduction
A number of fields ranging from the aerospace industry to atomic engineering require rapid and reliable methods for scanning, detecting and characterizing subsurface defects such as cracks, corrosion, air gaps and riveting failure in conductive multi-layered structures. In particular, corrosion is a critical problem for in-service aircraft structures which may lead to a degradation of structure intensity and fatigue resistance and directly affect the airworthiness of an aircraft and even result in loss of fuselage skin sections similar to the Aloha airlines incident of 1988 [1][2]. Eddy current testing (ECT) is presently used in aerospace for over 50\% of all applications for the detection of defects in fuselage skins and multi-layers and to clarify the real condition of aircraft structure for appropriate repair and corrective action [3]. However, the accurate characterisation of subsurface flaws in the conductive multi-layers still pose a major challenge and thus has been a research focus in the NDT fields [3][4].

In this paper, the forward model of ECT for scanning and inspecting defects on a multi-layered structure based on the finite element analysis (FEA) method is put forward. Using the ANSYS Parametric Design Language (APDL), simulation work is performed and the impedance responses of the probe coil due to defects of different length, depth locations and shapes are calculated. Experiments are carried out using the established ECT instrument combined with a scanner. The agreement between the calculated and experimental values is excellent and the techniques investigated can be used to quantify the parameters of defects.

2. Forward model
The numerical method used to calculate the impedance of a right cylindrical, air-cored eddy current coil during scanning over a multi-layered structure is based on the FEA model given by N. Ida et al [2][3].
Figure 1 shows the geometry of the system under study, consisting of a 2-layer structure and the flaws investigated have different length, locations, and shapes.

The eddy current problem can be described mathematically by the following partial differential equation (PDE) in terms of the magnetic vector potential [2][3]:

$$\nabla^2 A + k^2 A = -\mu J_s$$  \hspace{1cm} (1)

where, $A$ represents the magnetic vector potential, $\mu$ is the magnetic permeability of the media involved (H/m), $J_s$ is the excitation current density (Amp/m²), $k^2 = -j\omega \mu (\sigma + j\omega \varepsilon)$, $j$ is the imaginary unit, $\omega$ is the angular frequency of the excitation current (rad), $\sigma$ is the electrical conductivity (S/m), $\varepsilon$ is the dielectric constant (F/m).

Using the FEA method, the impedance of the multi turn coil is given by:

$$Z = \frac{j\omega 2\pi n}{I} \sum_{k=1}^{K} r_{ck} \Delta A_{ck} = \frac{j\omega 2\pi J}{I^2} \sum_{k=1}^{K} r_{ck} \Delta A_{ck}$$  \hspace{1cm} (2)

where, $Z$ is the impedance of the coil, $n_c$ is the turn density of the coil, $I$ is the current in a turn of the coil, $K$ is number of elements in the cross section of the coil, $r_{ck}$ is the distance from the element centroid to the symmetry axis, $\Delta A_{ck}$ is the area of element on the cross section of the coil, and $A_{ck}$ is the $A$ at the centroid.

The FEA method described above is applied to the scanning inspection simulation using the ANSYS software. The APDL is used to develop the simulation program so that the impedance of the scanning coil at different positions can be calculated automatically.

3. Simulation work

During the simulation the coil parameters are: inner radius $r_1=3.0$mm, outer radius $r_2=5.11$mm, length $l=20.7$mm, frequency $f=0.4$ kHz, liftoff (the distance from the bottom of the coil to the surface of the structure) $l_1=0.0$mm.

3.1. Simulation part 1: defects in different length

In this subsection, simulation is performed to inspect arc-shape defects of varying length in a two-layered structure (Figure 2). The properties of the layers are: the 1st layer: $\sigma=18.5$MS/m, $\mu=\mu_0=4\times10^{-7}$H/m, plate...
thickness \( t = 1.0 \text{mm} \). The 2nd layer: \( \sigma = 18.5 \text{MS/m}, \mu = \mu_0, t = 3.0 \text{mm} \). Arc-shape defect is located on the surface of the second layered simulating the corrosion of the double layered skin of an aircraft. Defect parameters: \( \sigma = 0 \text{ S/m}, \mu = \mu_0, L_{dy} \times L_{dz} = 15 \text{mm} \times 0.6 \text{mm} \). \( L_{dz} \) is ranging from 4mm to 52mm. Referenced to Figure 1, the initial position of the coil is (0, 0, 10.35) (mm), and the scanning distance is 80mm and the initial position of defect in the global coordinate system is (40, 0, -1.3). The length of defect are 4mm, 8mm, 12mm, ..., 52mm respectively (the step is 4mm). Simulation results are seen in Figure 3.

It can be seen that: When \( L_{dz} < 2r_t \), the impedance curve has a peak to valley. When \( L_{dz} > 2r_t \), the peak to valley disappears and becomes a peak.

With the relation curve of the reactance and resistance of the impedance, we find that the phase angle of each curve equals approximately to \( 145^\circ \) owing to the similar depth location of the defects.

3.2. Simulation part 2: defects at different depth locations
In this subsection we consider rectangle-shape defects at different depth locations (Figure 4). The properties and parameters of the structure and the coil are similar to those in Part 1. The parameters of defects are: \( L_{dx} \times L_{dy} \times L_{dz} = 80 \text{mm} \times 60 \text{mm} \times 0.6 \text{mm} \). The coordinates of the center point of the defects are (0, 60, -0.3), (0, 60, -1.3), (0, 60, -1.7), (0, 60, -2.7) respectively (corresponding to locations No. 1, 2, 3 and 4). The scanning range is 80mm and the simulation results are in Figure 5.

It can be seen in Figure 5 that we can identify and characterize defect parameters according to the impedance change and phase angle information.

3.3. Simulation part 3: defects of different shapes
The structure and defects considered are shown in Figure 6. \( L_{dx} \times L_{dy} \times L_{dz} = 40 \text{mm} \times 30 \text{mm} \times 1.0 \text{mm} \), the scanning range of the probe is 80mm. The coil impedance response due to defects of different shapes...
(rectangle, arc and wedge) is calculated respectively using the FEA program and the simulation results are shown in Figure 7.

We can see in Figure 7 that the phase angles of the three curves are almost the same because of the same depth location. The shapes of the impedance response curves are different and the profile of defects can be determined according to the impedance amplitude information.

### 4. Experiment

A schematic diagram of the experimental set-up is shown in Figure 8. Scanning inspections are carried out and experiment results for rectangle defects are shown in Figure 9. The structure studied is similar to the one in Simulation Part 2. The defects locate at Location 1 and Location 3 (See Figure 4). Probe scanning speed is 1mm/s, and data sampling frequency is 10Hz.

Figure 9 indicates that the experimental results have the same trend as the simulation ones and the location and other parameters of defects can be determined using the forward and experimental results.

### 5. Discussion and conclusions

The forward FEA model of ECT for probe scanning over a multi-layered structure has been developed. Simulation and experiments are carried out to inspect defects of different length, depth locations and shapes. The results obtained show that the parameters of defect in multi-layers can be quantified by using the impedance amplitude and phase information. Our future work is to optimize coil geometry and inspection system in terms of the simulation programs and to present an inversion procedure to estimate the profile of the defects.

### References

[1] C. L. Brooks, K. Honeycutt and S. Prost-Domskey 2000 Case studies for life assessments with age degradation. *The Fourth Joint DoD/FAA/NASA Conference on Aging Aircraft, St. Louis Mo (May)*

[2] N. Ida, R. Palanisamy, and W. Lord 1983 Eddy current probe design using finite element analysis. *Materials Evaluation, Nov.* pp 1389-94

[3] Wu Zhaotong, Huang Pingjie 2002 Impedance model simulation and verification of thickness multi-layered structure measurement using eddy current method. *Proceedings of the 4th Symposium on Metrological Science and Technology (Taiwan China)*

[4] Barend van den Bos, et al. 2000 Automatic scanning with multi-frequency eddy current on multilayered structures. *Proceedings of the 15th WCNDT (Rome: Oct)*