FREQUENCY OPTIMIZATION STUDIES WITH A MEANDERING COIL USING A 2D FINITE ELEMENT MODEL FOR EDDY CURRENT THERMOGRAPHY

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Abstract

Eddy current thermography technique is a relatively new NDE technique in which eddy currents are generated by virtue of electromagnetic induction within the specimen by introducing a current carrying coil in the vicinity. The approach that is adopted in this paper is giving a short heat pulse and monitoring the transient temperature profile of the surface owing to heat diffusion. Surface temperature is mapped using sensitive infrared camera. Unlike other active Thermography techniques, there is no need to carry large sized heating equipments which makes in situ inspections easy. Parameter optimization assumes importance in the context of bringing out better temperature contrasts. In this paper, by using a 2D finite element model based on induction heating by a meandering coil frequency optimization studies are conducted. The influences of current density on the optimum frequency and on the peak surface temperature are studied. Simulations were done based on parallel wires as well and the frequency values are compared. COMSOL multi physics software was used to solve the coupled equations of electromagnetic induction and heat transfer.

Keywords: Eddy current, Thermography, Current density, Induction heating, Finite Element Modeling

INTRODUCTION

Eddy Current Thermography is an Active Thermographic Inspection technique which utilizes the currents generated within a conducting specimen to facilitate the required temperature rise. Thermography is a well established Non Destructive Evaluation technique that examines the variations in temperature profile of a specimen’s surface for defect detection and characterization. The two modes of thermography includes (a) passive thermography, where the surface temperature of an object is measured without providing any external excitation, and (b) active thermography, where an external input is provided in the form of light, heat, or other means. In Eddy Current Thermography, the heat is generated within the specimen itself. The process of induction heating consists of development of eddy currents in a conducting material by electromagnetic induction and the consequent generation of heat by Joule heating. The heat diffuses in the material and the temperature on the surface of the specimen changes. The presence of an anomaly interferes with heat diffusion thus causing a local temperature contrast on the surface. Kumar et al. (2008) reported on the dependency of the heating on the frequency of the eddy current excitation, and compared eddy-current heating with conventional thermography method. The investigation in this direction was furthered by N. Biju et al (2009). The paper discusses the dependence of frequency on the thickness of the material, on the electrical conductivity, and on the amplitude of thermal response of the sample using an axi-symmetric finite element model. Depending on the frequency of excitation, the heating zone can be confined to the surface (surface heating) or to the entire volume of the material (volume heating). For both approaches, the efficiency of material heating and the subsequent retrieval of relevant information for the non-destructive
evaluation of materials and components require the use of optimum frequency for induction heating.

In the present paper, a 2-D finite element model is used and studies on optimum frequency were conducted so that anisotropic samples (which can be approximated as transversely isotropic) like unidirectional CFRP laminae can also be modeled. The variation of peak temperature with varying current densities has also been studied. Most endeavors made hitherto resort to axi-symmetric finite element modelling which cannot be used to optimize the frequencies in composite plates.

Further, the influence of coil geometry has also been studied to a small extend by choosing a meandering coil in one trial in which the direction of current reverses in every alternate coil and by choosing parallel wires carrying current in the same direction in another trial.

**DESCRIPTION OF THE 2D FINITE ELEMENT MODEL**

A 2D model is used in which the inductor is modeled as a wire that is oriented perpendicular to the 2D plane.

**Electromagnetic Induction**

The applied field and hence, the induced currents are both oriented in the z-direction. This implies that the magnetic field is present only in the modeling plane. Hence the magnetic potential has only one non-zero component, and it is possible to derive a second-order scalar Partial Differential Equation (PDE) for this case.

Considering the case when there are no variations in the z direction and the electric field is parallel to the z-axis. Then we can write

\[ \nabla V = -\frac{\Delta V}{L} \]

where \( \Delta V \) is the potential difference over the distance \( L \). Now the governing equation for time harmonic analysis becomes

\[ (j\omega\sigma - \varepsilon\omega^2)A_z + \nabla \times \frac{1}{\mu} \nabla \times A_z = (\sigma + j\omega\varepsilon) \frac{\Delta V}{L} + \vec{j}_{sz} \]

The boundary conditions are

Magnetic insulation at the outer domain boundaries.

\[ A_z = 0 \]

The relevant interface conditions are

\[ n \times (H_1 - H_2) = 0 \]

**Heat Transfer**

The heat diffusion equation in 2-D is in the form
\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \dot{Q} = \rho C_p \frac{\partial T}{\partial t}
\]

where the heat source \( \dot{Q} \) is the coupling term between the electromagnetic induction and heat transfer, and is given by

\[
\dot{Q} = \frac{1}{2} \sigma |E|^2
\]

The boundary conditions are

Prescribed temperature at the outer air domain boundaries.

\( T = T_0 \)

Convective and radiative heat flux from the coil and specimen surfaces

\[
-n \cdot (-k \nabla T) = q_0 + h(T - T_a) + \varepsilon \sigma (T_{a}^4 - T^4)
\]

**SIMULATION STUDIES**

Fig.1 shows the model used for simulation study. The coupled electromagnetic and temperature field equations were solved using COMSOL 3.5a multi physics software. Simulation studies were carried out for different current densities. In one study, a meandering coil was used which was simulated by positive and negative currents in alternate coils. Another study was conducted by considering the coils as individual wires running parallel carrying currents in the same direction, ie, all positive values. After different trials with different time durations of heating, a heating time of 3 seconds and a total period of observation of 8 seconds were arrived at. The material of the specimen was chosen as Aluminium. Both the coil and the specimen were placed in the air domain. In all the cases the lift off was kept constant.

![Simulation model](image)
Table 1- Material properties and constants

<table>
<thead>
<tr>
<th>Material property</th>
<th>Aluminium</th>
<th>Copper</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permeability</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical conductivity (S/m)</td>
<td>3.77×10⁷</td>
<td>5.998×10⁷</td>
<td>0</td>
</tr>
<tr>
<td>Specific heat (J/kgK)</td>
<td>900</td>
<td>385</td>
<td>1005</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2700</td>
<td>8700</td>
<td>1.23</td>
</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>160</td>
<td>400</td>
<td>0.026</td>
</tr>
</tbody>
</table>

The boundary conditions for electromagnetic induction were as follows:

1. Magnetic insulation at the air boundaries
2. Continuity of magnetic fields at the interior boundaries

Boundary conditions for the physics of heat transfer were as follows:

1. Temperature boundary condition at the air boundaries
2. Heat flux at the other boundaries

The temperature variation was monitored at the top centre of the specimen (Point P in fig 1) The same model was used to simulate parallel wires that carry current in the same direction by making appropriate changes in the sub domain settings.

RESULTS AND DISCUSSION

The temperature history of point P on the top surface of a 1mm thick Aluminium plate when meandering coil was used is shown in fig 2. There exists an optimum frequency for which the rise in temperature becomes maximum. The value of optimum frequency does not change with different time durations of heating. Only the peak temperature increases with increasing time duration of heating.

![Temperature history of point P on the top surface of the specimen with heating time 3 seconds](image-url)
The optimum frequency is independent of magnitude of current density. Here also it is the peak temperature that increases with current density. Fig 3 shows this. The values plotted correspond to the simulation with meandering coil. The heating pattern at the end of 3 seconds is shown as fig 4.

Owing to lift off and coil diameter requirements, a direct comparison with axi-symmetric model is not easy. Nevertheless when an axi-symmetric coil was used for the same specimen, the optimum frequency never came to more than 4 - 5 kHz. Simulation work by Biju et al yielded an optimum frequency value of 1.1 kHz using axi-symmetric coil.

By using parallel wires with current in the same direction, another value of optimum frequency was obtained that was considerably lower than that obtained using the meandering coil. A direct comparison can be made between the two. While in the former case it came in the range 6.5-7.0 kHz in the later it was in the vicinity of 65 kHz.
Apart from this change in the value of optimum frequency, the aforementioned results with meandering coil held good for this too as was expected.

**CONCLUSION**

Frequency optimization is achieved by the simulation of thermal field developed on the surface of a plate of conducting material due to inductive heating by a meandering coil on the basis of a 2-Dimensional finite element model.

The model can be effectively used to optimize frequencies while testing composite lamina such as CFRP where they can be approximated as transversely isotropic.

The optimum frequency was found to be independent of current density. It is also independent of pulse duration. The peak temperature increases with current density. It also increases with pulse duration.

Though a direct comparison is not possible with axi-symmetric coil, the optimum frequencies for various coil diameters and lift off distances were more or less close to those obtained by parallel uni-directional current coil system.

However, using meandering coil the optimum frequency in the case of a 1mm thick Aluminium plate was found to be significantly higher than that obtained while using a parallel wire system with current flowing in the same direction but with the same configuration and same coil dimensions for the same specimen. The optimum frequency using meandering coil was almost 10 times that obtained while using parallel coils with uni-directional current. This was true for all current densities.

**REFERENCES**