Eddy Current and Thermal Propagation for Quantitative NDT&E

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Abstract. As excitation factors of heating time and power directly affect the behaviour of eddy current and thermal propagation for eddy current pulsed thermography (ECPT), it is necessary to investigate the optimal parameters to maximize contrast between the defective and non-defective area as well as quantitative evaluation. The defect evaluation on complex geometry in the structural especially edges remains challenge due to multi-parameters effect. Suitable excitation factors are requested to edge structure detection for reducing the effects by complex geometry and improving the maximize contrast between the defective and non-defective. This paper researches the optimize excitation parameters strategy and demonstrate the positive effect for defect detection under these parameters. Under the premise of the uniform electromagnetic and thermal fields, the relationships between the excitation parameters and the physical mechanism are established by the separation of Joule heat via eddy current and thermal diffusion. The impact of the various parameters of excitation power and heating duration for edge detection is investigated. Appropriate stimulation current and heating period for promotion the detectability such as thermal contrast and SNR are reported, which will benefit to the quantitative evaluation of the defect detection.

1 Introduction

Eddy current pulsed thermography (ECPT) is one kind of inductive thermography which belongs to active infrared thermography[1]. It detects turbulence in conductive materials which combines the advantages of both pulsed eddy current and thermography testing [2]. The development history of ECPT experiences three stages: from 2005 to 2009, the different teams around the world dedicated to research the theory and simulation for the mechanism of induction thermography, and meanwhile, built the hardware platform [2-5]. From the beginning of 2009, due to rich time-spatial transient information of ECPT, it has attracted a wide range of industrial interests to classification and identification different defects for different fields such as in aerospace[6], marine structure[7], power system[8], renewable energy[9] and rail[10]. It strives to the process of standardization which expects to replace the well-established magnetic particle testing technique [11]. In recent years, it is increasing attention to utilize induction thermography to quantitative evaluation.

In ECPT, the difficulty of quantitative detection mainly derives from uneven excitation caused by complex geometries and material emissivity, image blur caused by the lateral thermal diffusion, low signal to noise ratio (SNR) of thermal image, the shield from excitation coil and so on. For this reason, optimization excitation parameters and advanced
signal processing technology are the two important aspects to breach the thermal quantitative detection. The optimization of excitation parameters can improve the uniformity of the electromagnetic and thermal field and provide a more effective incentive. For chosen the optimal parameters to maximize contrast between the defective and non-defective and improve SNR, previous researches have discussed the effect of inclination of the exciting coil for inspection of conductive plates[12]. N. Biju et al proposed the optimum frequency of eddy current excitation that will give a maximum temperature rise for a given thickness conductor[13]. Liu et al investigated the impact of thermal image sampling rates versus feature extraction for defect characterization. Appropriate sampling rates and the impact of using high end and low end thermal cameras for ECPT non-destructive evaluation are discussed[14]. Tsopelas et al determined the most effective of a coil when placed at an optimum distance from the plate, equal to 1/4 of the diameter for a circular coil or 1/4 of the side for a square coil. The detection range and detection period depend on the crack orientation with respect to the heat flow, the magnetic flux density and the heating time[15-16]. J. Vrana et al discussed the coupling and optimization strategies for different thermal systems[17]. Jelinek M explored the methodological deduction to improve the optimization thermographic systematic parameter and the structured parameter of test specimens for CFRP[18]. Crinière A discussed the optimal heat duration of square pulsed excitation to improve the detectability[19]. The research method of the above parametric studies, changing the excitation parameters to discuss the detection results, is effective. However, the previous research rarely adopts theoretical guidance to optimize selection strategy of the excitation parameters.

Under the premise of the uniform electromagnetic and thermal fields, this paper establishes the relationships between the excitation parameters and the eddy current and thermal patterns through the separation of Joule heat via eddy current and thermal diffusion. The impact of the various parameters of excitation power and heating duration for edge detection with complex geometry is investigated. Appropriate stimulation current and heating period for promotion the detectability such as thermal contrast and SNR are reported.

2 Eddy Current Pulsed Thermography

2.1 System introduction

Fig. 1 shows the schematic diagram of ECPT. The synchronized trigger control IR camera and induction heating element to simultaneously turn-on and turn-off. The induction heating element generates a high frequency current excitation signal continuing few milliseconds. It is driven to the transmitter coil above the conductor which will induce the eddy currents and generate the resistive heat in the conductive material. It is automatically impedance matching between the coil and excitation source via excitation frequency. Thus,
when the coil is selected, the excitation frequency also will be determined. In the whole physical process, the three dimensional thermal diffusion leads the heat flow from high to low temperature area, and then reduces the contrast till the heat balance in material. If a defect exists in conductive material, the distribution of eddy current or the process of thermal diffusion will be disturbance. Consequently, the resultant surface heat distribution and the transient temperature time spatial response will show the variation captured by an infrared camera.

2.2 Background theory

The main physical process of ECPT are involved by induced eddy currents heating and thermal diffusion. Heat conduction equation connects with electromagnetic and thermal fields each other which is derived by Fourier's law and energy conservation law.

The differential form of Fourier's Law of thermal conduction can be written as:

\[ q = -k \cdot \nabla T \]  

where \( q \) is the local heat flux density which is the amount of energy that flows through a unit area per unit time. \( k \) is the material's conductivity. \( \nabla T \) is the temperature gradient. According to energy conservation law, inductive heat conduction equation merged with Joule heating and thermal diffusion can be expressed as:

\[ \frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{1}{\rho C_p} q(x, y, z, t) \]  

where \( T = T(x, y, z, t) \) is the transient surface temperature distribution, \( \rho \) is the density (kg/m³), \( C_p \) is specific heat capacity (J/kg K), and \( q(x, y, z, t) \) is the heat generation function per unit volume and unit time, which is the result of the Joule heating which is the coupling of the electromagnetic and thermal fields. The following equation expresses this relationship:

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

where \( E \) is the electric field intensity, \( \sigma \) is the electrical conductivity, \( J_s \) is the external current density. The eddy current distribution could be expressed from the electromagnetic governing equation:

\[ \frac{1}{\mu} \nabla^2 A + \sigma \frac{\partial A}{\partial t} = J_s \]  

where \( \mu \) is the magnetic permeability, \( A \) is vector potential. In the depth direction, eddy current density meets the following conditions:

\[ J_e(z) = J_e(0) \cdot e^{-z/\sqrt{\pi \mu \sigma \tau}} \]  

where \( Z \) represents depth. \( J_e(0) \) shows the surface eddy current density and it decays exponentially towards the interior of the conducting media, falling to 1/e of the value at the surface in a distance called the skin depth \( \delta \):

\[ \delta = \frac{1}{\sqrt{\pi \mu \sigma \tau}} \]  

In previous work[20], we constructs a physical-mathematical time-dependent partition model to analyse the whole thermal transient process and consider characteristic times for separating Joule heating and thermal diffusion into four different stage. In the present work, in order to improve the detectability, the relationships between the excitation parameters and physical mechanism will be build through above physical model.
3 Results and Discussion

3.1 Experimental Setup

The appropriate excitation parameters should heat the specimen sufficiently without damaging. To ensure the heating efficiency with limited resources, the numerical analysis could provide an efficient way for achieving the target. The discussion of heat period and excitation power is based on the separation of electromagnetic and thermal field.

In previous work[21], compared to straight wire, the optimal parameters of Helmholtz coils for edge structure detection had been discussed, which provides a uniform electromagnetic/thermal field to guarantee the following excitation parameters discussion shown in Fig.2. Finite element method (FEM) for EC and temperature distribution were performed using COMSOL Multiphysics simulation software via the electro-thermal module which combines the application mode for induction currents and general heat transfer. In the simulation, an isotropic structural steel sample with geometry of 60 mm × 30 mm × 5 mm(height*width*depth) is modelled. The size of crack in steel is 10mm*0.35mm*5mm. The electrical and thermal parameters for the steel used in these simulations are shown in Table 1. The relationship between excitation parameters and physical mechanism will be built.

![Fig 2 Finite element mesh model for edge structure defect and Helmholtz coils](image)

3.2 Optimal Parameters of Excitation Power and Heating Duration

The main goal of discussion of ECPT excitation parameters is to obtain a high thermal contrast to improve the quantitative detection. From the aspect of physical mechanism, the effects of the optimal parameters of excitation time and heating power are undertaken by creating an optimization interval for each parameter.

The observed area is chosen from the same place through this part. The size and shape of the observed area are selected by human annotation. The temperature profile which take the average of the temperature of all pixels in the observed area through the whole ECPT video is depicted in Fig 3,4 and 5 (a). Fig 3,4 and 5(b) shows the first derivative of temperature against time dT/dt-t. According to the physical separation mechanism[20], the isolate parts of eddy current and thermal diffusion are shown in Fig 3,4 and 5(c). Because the emissivity of the sample is unknown, digital level (dl) is used to describe the temperature rather than Celsius degree(℃).

1) Discuss heating time and cooling time

To impact the excitation time, the heating power are fixed(300A) and varied the excitation time from 200ms to 600ms. With the longer of the excitation time, the eddy current density is unchanged on account of the constant excitation energy. The surface temperature of the observed area is rise(Fig 3.(a)). From Fig 3.(b) the result of the first derivative of temperature against time shows that temperature gradient will reduce and stabilize at a positive value close to zero at the end of the heating stage. This means Joule heating by eddy current and thermal diffusion achieve a balance shown in Fig3(c).
Meanwhile, the thermal diffusion from the heating and cooling stage is reciprocal. In Fig3.(c), after derivation the curve of thermal diffusion form the heating and cooling stage respectively, the two parts of curve are almost equal in the case of absolute value.

Table 1. Electrical and thermal parameters for steel used in the simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conductivity, $\sigma$ (S/m)</th>
<th>Relative permeability, $\mu$</th>
<th>Temperature coefficient (K-1)</th>
<th>Density, d(kg/m³)</th>
<th>Heat capacity, $C_p$ (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>4.0319×10^6</td>
<td>100</td>
<td>12.3×10^-6</td>
<td>7850</td>
<td>475</td>
</tr>
</tbody>
</table>

The numerical results clearly suggest that the cooling time should be the same as the heating time due to the rotationally symmetrical of thermal propagation between heating and cooling stages. The range of heating time should begin when the eddy current and thermal diffusion tends to balance. After that, the surface temperature increases linearly under heating time growth. It also should be considered the thermal sensitivity of the camera and the heat-resistant degree of the material in real experiment.

2) Discuss the different excitation power

To determine the heating power, the excitation time is fixed(400ms) and varied the excitation power from 100A to 300A. Surface temperature increase is proportional to the factors of excitation power (Fig 4.(a)). From Fig 4.(b) and (c), the results show that the higher excitation power is, the more severe thermal diffusion is. According to the Fourier's Law, the reason is that the larger temperature difference lead to a greater rate of heat propagation. In Fig 4.(d), the min-max normalization process makes the data mapped to the range [0, 1]. It shows that the three curves almost completely overlap. The important interpretation from Fig 4(d) is that, as the excitation current increases, the thermal diffusion did not reach saturation which shows linear growth. This indicates that, without damage of specimen, excitation current should be apt to the larger one in experiment.
Fig. 4 Compared different excitation power: (a) transient temperature response against time, (b) 1st derivatives of temperature response, and (c) physical separation of eddy current and thermal diffusion, (d) the normalization of the physical separation for various excitation power.

3) Discuss the multi parameters (heating during $\times$ excitation power)

To comprehensive consideration of the excitation parameters, the excitation energy is constant and varied the excitation time from 200ms to 600ms and current from 300A to 100A. In Fig 5, the results show that, the temperature rise is rapid and all of the curves are relatively steep under temporal large current; when the duration of heating period becomes longer and excitation power turns into smaller, the slope of the temperature rise gradually decreases and the thermal diffusion curve becomes gentle. When the specimen obtains larger instantaneous energy, it is more obvious to capture the turbulence because the intense thermal diffusion will easily distinguish between defect and non-defective region. However, more energy conducted into the specimen may cause thermal impact damage in particular for composites. As a reminder, when the use of heat sources such as lasers and microwaves with extremely short duration or very high frequency, the classical Fourier's heat conduction theory becomes inaccurate and the non-Fourier effect becomes more reliable in describing the diffusion process and predicting the temperature distribution[23].

This part discussed three factors of excitation parameters: heating and cooling time, excitation power and comprehensive consideration between these two elements through the electromagnetic and thermal fields, respectively. The strategy of optimal excitation parameters will display the positive effect to the detectability and quantitative analysis.
3.3 The influence for quantitative defect analysis

In order to discuss optimal excitation parameters for the advantage of quantitative defect detection, finite element model are established. The thermal sensitivity and SNR utilize to assess the detection results by four groups of various parameters.

The definition of thermal contrast [22] is to measures the difference between defective and non-defective regions. In Fig 6(a), An area in the defect that will be considered as “signal” (Sarea) and an sound area as a non-defective region around the defect defined as “noise” (Narea).

\[
\Delta T(t) = T_{\text{Sarea}}(t) - T_{\text{Narea}}(t)
\]  (7)

Where \(\Delta T(t)\) is the thermal contrast. \(T_{\text{Sarea}}(t)\) is the temperature of the defect area. \(T_{\text{Narea}}(t)\) is the reference temperature area. The calculation of the SNR value comes from[22]:

\[
SNR = \frac{S}{N} = 20 \log_{10} \left( \frac{\text{abs}\left(S_{\text{mean}} - N_{\text{mean}}\right)}{\sigma} \right) [dB]
\]  (8)

where \(\sigma\) is the standard deviation of the noise and \(S_{\text{mean}}\) and \(N_{\text{mean}}\) are the average temperature values of each area, respectively.

<table>
<thead>
<tr>
<th>Power(A)</th>
<th>SNR(dB)</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>-5.97</td>
<td>-3.84</td>
<td>5.62</td>
<td>12.94</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>-6.02</td>
<td>-3.82</td>
<td>5.73</td>
<td>13.06</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>-6.05</td>
<td>-3.88</td>
<td>5.96</td>
<td>13.23</td>
<td></td>
</tr>
</tbody>
</table>

According to the Fig.6(b),(c) and Table 2, the results show that changing the excitation period has a little effect to the detection. The high excitation current have the better performance on the detectability ( thermal contrast and SNR). The reason is that the increase of the exciting current does not change the distribution of eddy current. Therefore, in other
conditions remain unchanged, the high excitation energy will generate the high surface temperature, and also lead to high thermal contrast which will benefit to the quantitative defects detection.

### 4 Conclusion

The parametric study results obtained allow understanding the degree of impact of various elements on the induction heating setup during NDE induction thermography. Adjustment excitation power and heating time will affect the generated temperature profile and heating efficiency in the test pieces. On the basis of the uniform electromagnetic and thermal fields, this research establishes the link between physical mechanism and excitation parameters of ECPT. The optimal selection strategy of heating duration and excitation power is that: the mark of the beginning of the heating time interval is the balance of the eddy current and thermal diffusion. The cooling time should be the same as the heating time. Without damage of specimen, excitation current should be apt to the bigger one in experiment. With respect to the long-term low current excitation, temporal large current can get better detection results. The high excitation current have the better performance on the detectability (thermal contrast and SNR). However, increase the excitation period has a little effect to the detection. The optimal excitation parameters will benefit to the quantitative evaluation.

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