

ELECTRO-THERMAL MODELING AND MATLAB-SIMULINK SIMULATION OF LOCK-IN THERMOGRAPHY FOR NON-DESTRUCTIVE CHARACTERISATION

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Abstract: This paper proposes and validates a novel simulation for thermal non-destructive characterization. An electro-thermal modelling of the sample is adapted for MATLAB - SIMULINK simulation. Though the technique is capable of considering any heat stimuli on an arbitrary sample, the special case of lock-in thermography (LT) with periodic heating is taken up for illustration. A mild-steel sample having defects at different depths is taken as a test sample. Phase of the reflected thermal wave having great importance in LT, is obtained by measuring time delay of the reflected thermal wave. Predictions from the proposed simulation technique are shown to match well with experimental results.

Introduction: Presently two different types of active thermography [1] are mainly in use: Pulse and Lock-in thermography. In pulse thermography, the examined material is warmed up with a short energy pulse (light, eddy current, or ultrasonic pulse) and the thermal response recorded with time. The resultant infrared image sequence indicates material defects at different depths, but it is also affected by local in-homogeneities of the material surface as well as non-uniform heating. Lock-in thermography uses sinusoidal intensity modulated thermal excitation in order to derive information from the observed phase and magnitude of reflected thermal wave. The phase angle has the advantage that it is independent of local variations of illumination or of surface emissivity.

The present work describes a MATLAB-SIMULINK [2] simulation for lock-in thermography. The defect depth is estimated by measuring the phase of the reflected thermal wave. Simulated results show good match with experimental results.

The basic concept of Lock-in thermography is the periodic heating of the sample surface by a sinusoidal intensity modulated heat source as shown in Fig.1. This causes a heat distribution to propagate into the material. Reflection of the thermal wave is caused, if it finds a different thermal impedance medium. For the purpose of analysis, the sample is considered as semi-infinite, on to which a uniform heat source periodically deposits heat at a modulating angular frequency ω . Then, neglecting convection losses, the temperature T , as a function of depth z and time t is given by [3],

$$T(z, t) = T_0 e^{-(z/\mu)} \cos(2\pi z/\lambda - \omega t) \quad (1)$$

where

T_0 is amplitude of the oscillating temperature, z the depth below the surface, λ is the wavelength of thermal wave, ω the angular frequency and μ is the thermal diffusion length [3], defined as follows

$$\mu = \lambda/2\pi = [2\alpha/\omega]^{1/2} \quad (2)$$

where α is thermal diffusivity of the material. The depth of penetration μ of thermal waves in a given material (thermal depth range) is therefore dependent not only on the material properties but also on the modulating frequency of the heat source. The smaller the modulation frequency, the deeper is the penetration of the thermal wave.

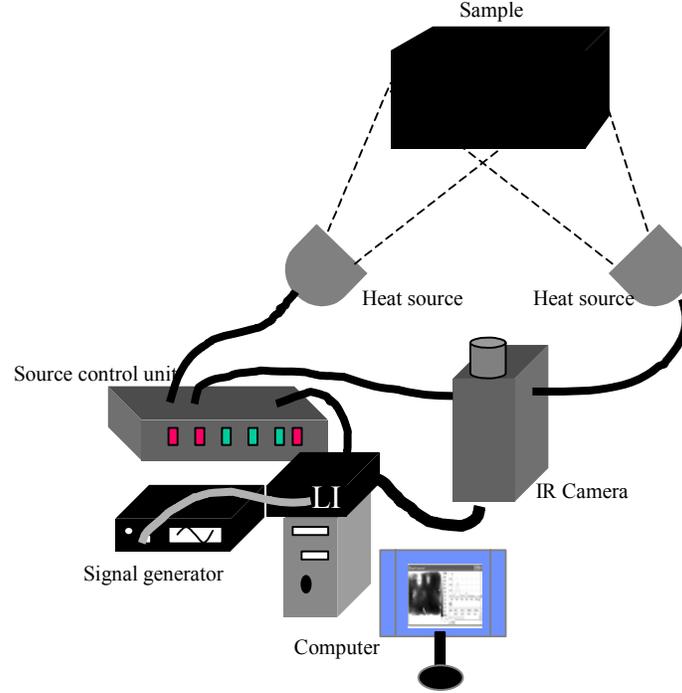


Fig.1. Schematic of employed lock-in thermographic NDT system for detection of defects.

Extraction of magnitude and phase information in lock-in thermography [4,5] is obtained by phase shifting method as follows. Let A_1 and A_2 are the amplitudes of incident and reflected thermal waves, respectively, and then resultant intensity (A_{res}^2) on the sample surface because of the superposition of the incident and reflected thermal waves is given by

$$A_{res}^2 = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\varphi) \quad (3)$$

In a given heating cycle, four samples can be taken, each 90 degrees apart, $A_{res(0)}^2$, $A_{res(90)}^2$, $A_{res(180)}^2$ and $A_{res(270)}^2$, respectively.

$$A_{res(0)}^2 = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\varphi) \quad (4)$$

$$A_{res(90)}^2 = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\varphi+90) \quad (5)$$

$$A_{res(180)}^2 = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\varphi+180) \quad (6)$$

$$A_{res(270)}^2 = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\varphi+270) \quad (7)$$

Magnitude and phase of the reflected thermal waves are then obtained as follows:

$$\text{Magnitude} = \text{Sqrt}([A_{res(0)} - A_{res(180)}]^2 + [A_{res(90)} - A_{res(270)}]^2) \quad (8)$$

$$\text{Phase} = [A_{res(0)} - A_{res(180)}] / [A_{res(90)} - A_{res(270)}] \quad (9)$$

Signal to noise ratio in lock-in thermography can be improved by averaging over more than cycle.

Results: In this section the electro-thermal model is developed and based on it results of the MATLAB-SIMULINK simulations for lock-in thermography are presented.

Electro-Thermal Modelling: Traditionally, in electro-thermal modelling, the RC equivalent [1] of a material sample is calculated using the equivalence between the fundamental laws of heat and electricity, such that heat transfer problems can be associated with electrical circuits. Consider a heat-conducting solid, the ends of which are maintained at different temperatures T_1 and T_2 . The Fourier law relates the heat flow to the gradient of the temperature,

$$q = -k \text{ grad}(T) \text{ J/m}^2\text{-sec} \quad (10)$$

where q is the heat flow per second per unit area and k is the thermal conductivity. The form of this law is identical with ohm's law for the flow of electric charge, which relates the current density with the gradient of electrical potential. For a sample of length L (m) and cross sectional area A (m^2) normal to the direction of heat flow Q (J/sec), Eq. (10) can be expanded as

$$Q/A = k(T_1 - T_2)/L \quad (11)$$

$$Q = (kA/L)(T_1 - T_2) \quad (12)$$

Heat supplied to a system raises the internal energy, according to the relation $C_i(dT/dt) = Q$ (J/sec), where C_i is the thermal capacitance (J/deg), and can be written directly as

$$C_i = MC_p \quad (13)$$

M being the mass of the block (kg), and C_p is the specific heat at constant pressure (J/deg·kg).

The thermal, electrical equivalent values of the resistance (R) and capacitance (C) of mild steel sample (Fig.2(a)) are calculated using Eqs. (12) and (13),

$$R = L / (k * A) \quad (14)$$

$$C = \rho * c * L * A \quad (15)$$

ρ being the density of the material (kg/m³).

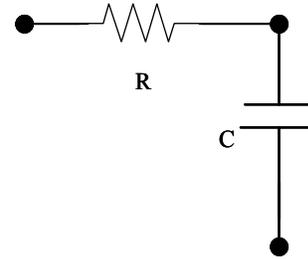
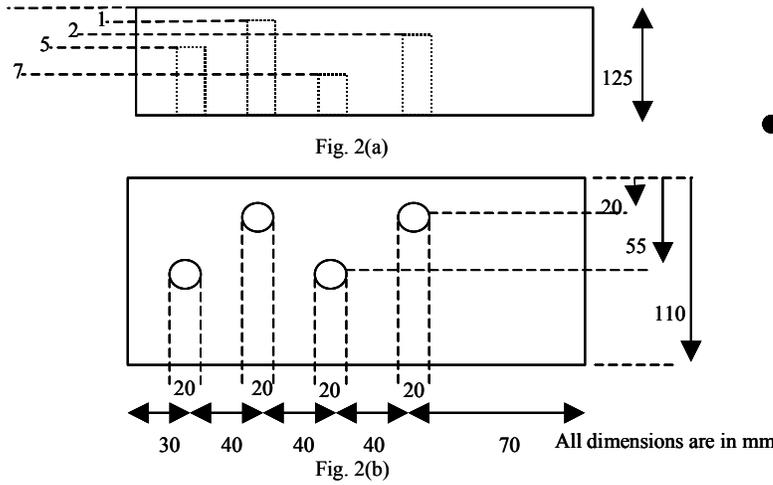


Fig.2. (a) and (b) shows side and top view, respectively of the mild steel specimen with artificial flat bottom hole defects, (c) shows the electrical equivalent for any one of the given defects.

The above electro-thermal modeling of the mild steel sample with defects shows that it acts as a low pass filter. Consequently, the phase and magnitude of the reflected thermal wave can be easily calculated from the transfer function of a low pass RC filter, $H(j\omega) = [1/j\omega C / (R + 1/j\omega C)]$. The magnitude $|H(j\omega)|$ of the reflected thermal wave is therefore,

$$|H(j\omega)| = 1 / [\text{Sqrt}(1 + (f/f_c)^2)] \quad (16)$$

Where f is the driving frequency of the heat source and f_c the cut-off frequency (3-db) for the above RC filter is defined as

$$f_c = 1/2\pi RC \quad (17)$$

f_c is the maximum usable frequency for a given defect depth for a specific material. The phase (Φ) of the reflected thermal wave can also be obtained as

$$\Phi = \tan^{-1}(f/f_c) \quad (18)$$

MATLAB-SIMULINK Simulation: Fig.3. shows the electrical equivalent of a sample undergoing lock-in thermography. Here the R , C values are calculated using eqns. 14, 15 for the mild steel sample of thickness 13 mm. Defects in the form of blind holes are introduced at known depths from the front surface at 1mm, 2mm, 5mm and 7mm. Incident oscillating temperature due to active heating is represented by a controlled voltage source outputting a sinusoidal voltage of 10Volts. For a given defect depth two RC sections have been considered; the first representing the transmitted thermal wave and the second section representing the reflected thermal wave. The interference between the reflected and the incident thermal waves is represented by an equivalent

mathematical analogy implementing eq. 3, in the simulation by taking the output of controlled voltage source and the output of the Fig.3.

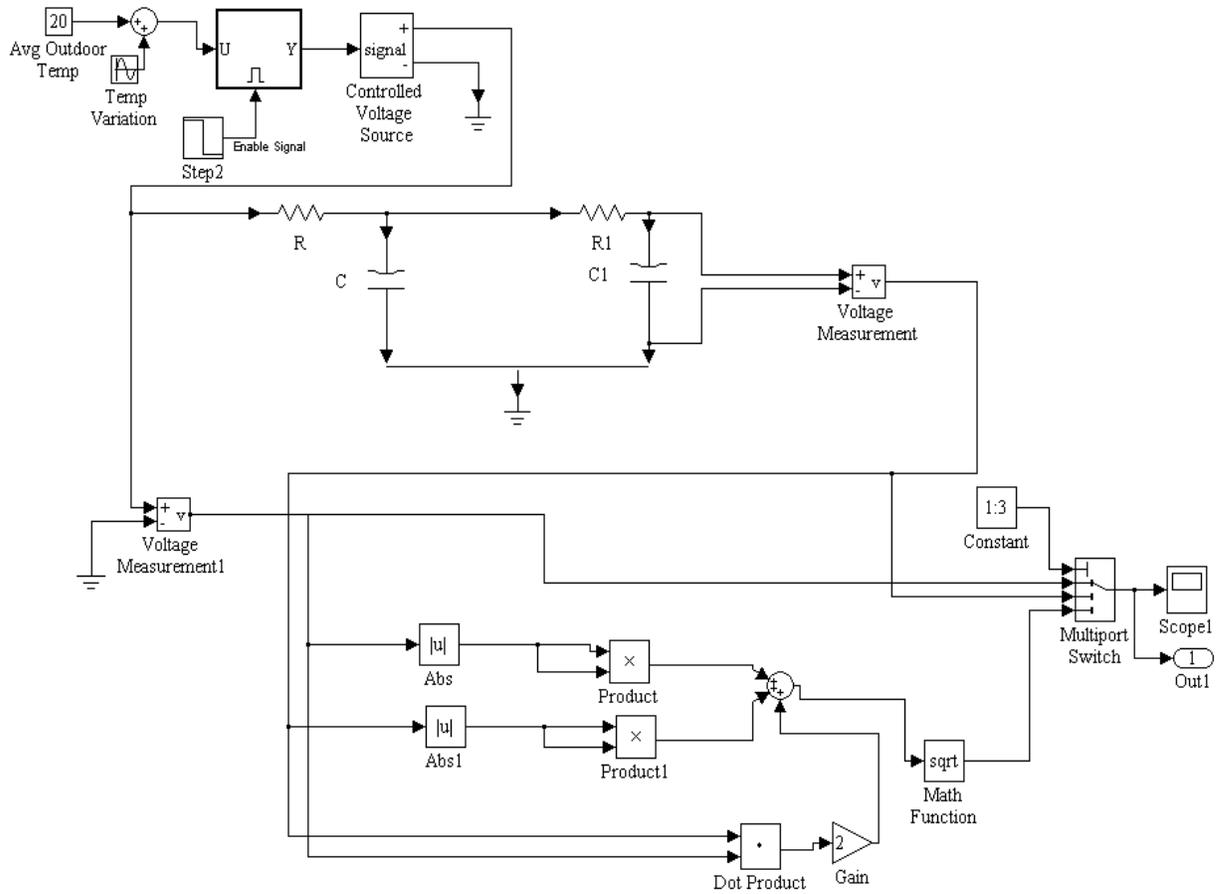


Fig.3. Equivalent circuit of a sample undergoing lock-in thermography for any one of the given defects.

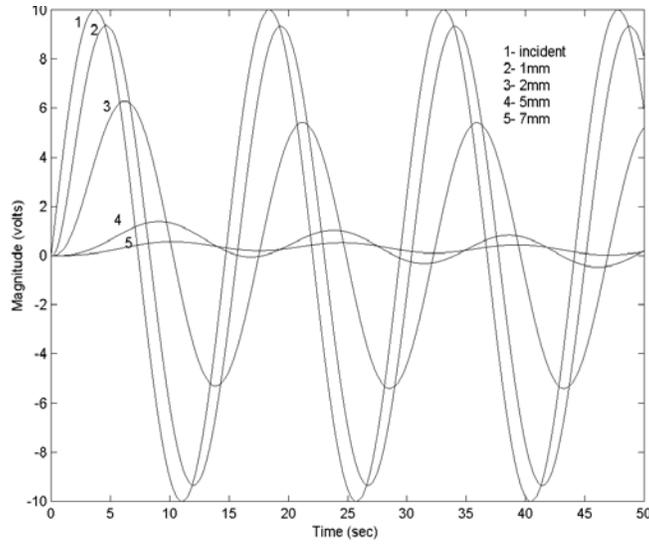


Fig.4. Time delay of the reflected thermal wave from different depths.

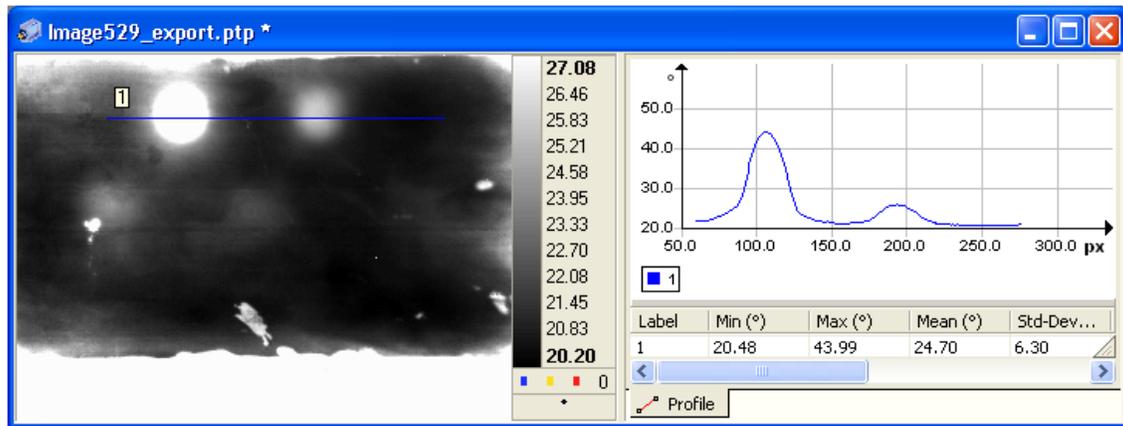


Fig.5. Phase images of lock-in thermography at 0.068 Hz.

Defect depth in mm	Difference in depth(mm)	Phase (degree) (Simulated)	Phase (degree) (Experimental)
1	2-1=1	21	20
2			

Table I. Comparison between simulated and experimental phase values at $f=0.068$ Hz

Discussions: An important aspect to be taken into account is that for the specified defect depths the driving frequency should be less than the cut-off frequency. This amounts to saying that for specified depths appropriate cut-off frequency needs to be calculated separately.

For the 1 mm and 2 mm deep defects, the calculated cut-off frequencies from eq. 17 are 0.4733 Hz and 0.1183 Hz, respectively. Whereas, for defects 5 and 7 mm the calculated cut-off frequencies are 0.0189 Hz and 0.0096 Hz, respectively. But the heat sources used in the experimentation can be driven at a minimum of 0.01 Hz frequency. Therefore because of this experimental limitation comparison has been made only for the defects whose cut-off frequencies are below 0.01 Hz. The present work therefore focuses only on defects, which are at 1 mm and 2 mm depths, respectively.

CEDIP JADE II infrared camera (3 μm -5 μm) has been used for experiments. Lock-in has been carried out by averaging over four cycles for improving the signal to noise ratio. Fig. 4. shows the simulated time delay of the reflected thermal wave at 0.068Hz frequency, from different depths. It is clearly noticeable that the thermal wave gets highly damped with increasing depth. Table I shows the comparison between the simulated and experimental phase values, which shows a good match between the MATLAB-Simulink simulation based on electro-thermal modelling and experimentally (Fig.5.) obtained phase values. It may be noted that the image in Fig.5. also shows the 5 mm and 7 mm deep defects, indicating that the phase images having the ability to go deep enough (almost twice the diffusion length) for detecting the defects, and are also insensitive to surface in-homogeneities and non-uniform sample heating [4].

Conclusions: In the presented approach, electro-thermal modeling of the sample is adapted for Lock-in-thermography and the effect of the frequency dependent thermal diffusion length for defect depth estimation is studied by assuming the mild steel sample to behave like a low pass filter. Simulations have been carried out using MATLAB – SIMULINK, a popular block-orientated program that allows simulating and analyzing dynamic, multi-domain, linear and continuous systems. By choosing the driving frequency of heat source below the cutoff frequency (decided by the sample thickness and/or defect depth) of the RC network one can easily estimate the defect depth. Comparison between experimental and simulation results shows a good match of phase for given defect depth.

References:

- [1]. XAVIER P V MALDAGUE, *Theory and Practice of Infrared Thermography for Non-destructive Testing*, Wiley-Interscience Publication, John Wiley & Sons, Inc. (2001).
- [2]. Simulink, *MATLAB/Simulink*. The Math Works Inc., Natick, Mass. 01760, U.S.A., 1st ed. (1993).
- [3]. X. Maldague F. Galmiche and A. Ziadi, “Advances in pulsed phase thermography”, *Infrared physics & Technology*, 43 175-181 (2002).
- [4]. B.S.Wong, C.G. Tui, W.Bai, P.H. Tan, B.S. Low and K.S. Tan, Thermographic evaluation of defects in composite materials, *Insight*, Vol. 41, No. 8, Aug. 1999.
- [5]. Datong Wu and Gerd Busse, “Lock-in thermography for nondestructive evaluation of materials”, *Rev. Gen. Therm.*, 37, 693-703 (1998).

