Thermo-graphic Detection of Surface Cracks

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ABSTRACT

This paper describes a thermal gradient method for infrared thermography to detect surface crack in thin plate. Traditional thermal gradient method uses a derivative of thermal field, which may magnify a noise inevitable in experimental thermography induced mainly by emissivity variation of target surface. This study develops a thermal gradient method robust to the noise using a holomorphic function of temperature field in a thin plate under steady-state thermal condition. The holomorphic function of a given temperature field is derived for 2-D heat flow in the plate from Cauchy-Riemann conditions,and applied to define a contour integral that varies according to the existence and strength of a singularity in the domain of integration. The integral calculated at each point of thermal image eliminates the temperature variation due to heat conduction and suppress the noise, so that its image emphasizes and highlights the singularity such as crack. This feature of holomorphic function is investigated numerically using a thermal field in thin plate that satisfies the Laplace equation representing steady-state heat flow. The simulation results show that the integral image selects and indicates asingularity like crack embedded artificially in the plate very well in a noisy environment.

Introduction

Active thermography including optically or inductively heated thermography offersanon-contact and rapid inspection method that detects flaws set in a plane parallel to the surface such asdelaminations and impact damage in composite materials or multilayered structures.Active thermography technique has been employed successfully to increase its sensitivity and image contrast of active thermography for defects in a specimen that has nonhomogeneous emissivity or irregular surface.However, the conventional approach of active heating a wide area of an object, using high power flash lamps, is not effective for the detection of surface cracks that develop perpendicular to the surface. The detection of such cracks in metallic components is a major concern for thesteel manufacturing and automobile industry. While traditional NDT techniques such as ultrasonics and eddy currents are used in the industry, there has been an increasing interest in investigating the potential of thermographic based techniques to provide more rapid, efficient and convenient inspection methods. Infrared thermography techniques (IRT) have been developed to detect surface cracks combining thermography with laser scanning and pulsed eddy current. Sakagami[1,2] introduced a new induction IRT technique termed "singular method" for crack identification. In the singular method, cracks are identified from the singular electro-thermal field generated around the crack tips, and concentrated temperature rise is observed in the vicinity of the crack tips. When a periodically modulated electric current is applied to the cracked sample, the intensity of the singular current field oscillates in the same frequency. This cyclic change of the singular electro-thermal field results in the cyclically changing temperature distribution, which can be imaged by the lock-in mode using the reference signal ofthe modulated electric current. Almond[3], Nezelmann[4], and Zenzinger[5] calculated the current distribution induced by external coilto investigate current flow near the surface of specimen, current density around a crack, how much heat is produced and diffused at the location ofthe crack. They can detect the cracks by direct observation of the heating process due to concentrated current density and a modification of the heat diffusion. Also Holland[6] visualized surface crack by employing vibration induced frictional heating of the crack in titanium. A laser scanning technique combined with thermography was developed and proved to be very successful to find surface crack by Li[7]. The method uses a laser heat source such as Nd:YAG laser for a local excitation on specimen, where the resulting surface temperature is recorded with an infrared camera. The beam is focused on the test sample by using an optical scanner to generate the required lateral heat flow. The time resolved temperature distribution is recorded with a high-speed infrared camera. Based on this data, crack-caused anisotropies in the lateral heat flow can be detected and exploited to characterize the cracks. Another approach to detect surface crack is forced diffusion thermography proposed by Lesniak[8]. It projects a pattern of dynamic heat to force the flow across the crack thereby optimizing measureable thermal gradient. The basic idea is that the heat flow is impeded by the crack creating a gradient in the thermal image, which clearly defines the crack. Since gradients caused by emissivity variance from the surface can be misconstrued as cracks, the thermal spatial derivative of crack was employed by applying two opposing heat flows to the specimen to separate the flaw image from noise (emissivity variance). However, the derivative of thermal image magnifies the noise from many sources so much that the gradient image does not always provide better information than raw thermal image.

This paper proposes a new thermal gradient method to define and locate surface crack from noisy thermal image obtained in a thin plate. This method uses the holomorphic function of temperature field in the plate under steady-state thermal condition to enhance the crack profile out of the noisy image. It is derived for 2-D heat flow in the plate from Cauchy-Riemann conditions, and applied to define a contour integral that varies according to the existence and strength of a singularity in the domain of integration. A theoretical formulation for the holomorphic function is made and implemented to set up an integral model that provides a numerical algorithm for data processing. An artificial crack-like singularity is created in the plate model to investigate the performance of the method.

Heat equation in plate

Heat conduction in a thin plate is governed by the two dimensional heat conduction (diffusion) equation in absence of heat source in the domain of interest[9],

$$\frac{\partial T(x,y,t)}{\partial t} = \alpha \cdot \nabla^2 T(x,y,t) = \alpha \left[\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2} \right] \tag{1}$$

$$\alpha = \frac{k}{\rho c_p} \text{(Thermal Diffusivity)}$$

Where T is temperature, k is thermal conductivity, and ? is thermal diffusivity. In the time independent case, i.e. $\frac{\partial T}{\partial t} = 0$, the heat equation of Eq. (1) reduces to

$$\nabla^2 T(x,y,t) = \left[\frac{\partial^2 T(x,y,t)}{\partial x^2} + \frac{\partial^2 T(x,y,t)}{\partial y^2} \right] = 0 \tag{2}$$

This Laplace equation of Eq.(2) is satisfied wherever in the domain when a steady state is reached without heat source. Exact solution to Eq. (2) is already known as holomorphic function (or analytic function) in complex analysis. If the temperature distribution is a real valued function of the complex function $f(x+iy)$, i.e., $F(x+iy) = T(x,y) + i\Theta(x,y)$, where $\Theta(x,y)$ is the conjugate harmonic function of $T(x,y)$, then $T(x,y)$ automatically satisfies the Laplace equation given in Eq. (2) only if the function $f(x+iy)$ is analytic. The Cauchy-Riemann equations corresponding to the function $f(x+iy)$ state

$$\frac{\partial T}{\partial x} = \frac{\partial \Theta}{\partial y}, \quad \frac{\partial T}{\partial y} = -\frac{\partial \Theta}{\partial x} \tag{3}$$

Thus, the increment of conjugate harmonic function is expressed in terms of by

$$d\Theta(x,y) = -T_y(x,y)dx + T_x(x,y)dy \tag{4}$$

Let $f(z) = f(x+iy)$ is a holomorphic function defined over adomain D. Then

$$\int_C d\Theta = 0 \tag{5}$$

The integrability condition of Eq. (5) implies that the value of the contour integral surrounding the domain Sis zero as shown in Fig. 1.This condition is always valid locally unless the line C does not loop around a singularity.

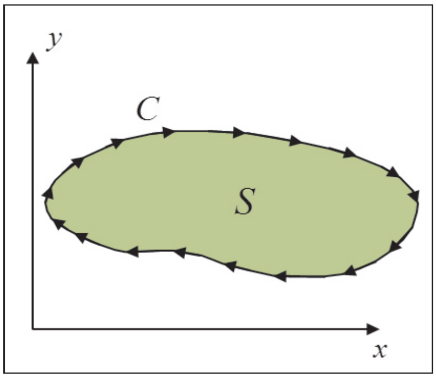


Fig. 1: Contour integral along C

Then, from Eq. (5) and Stokes' theorem,

$$\int_C d\Theta = 0 \tag{6}$$

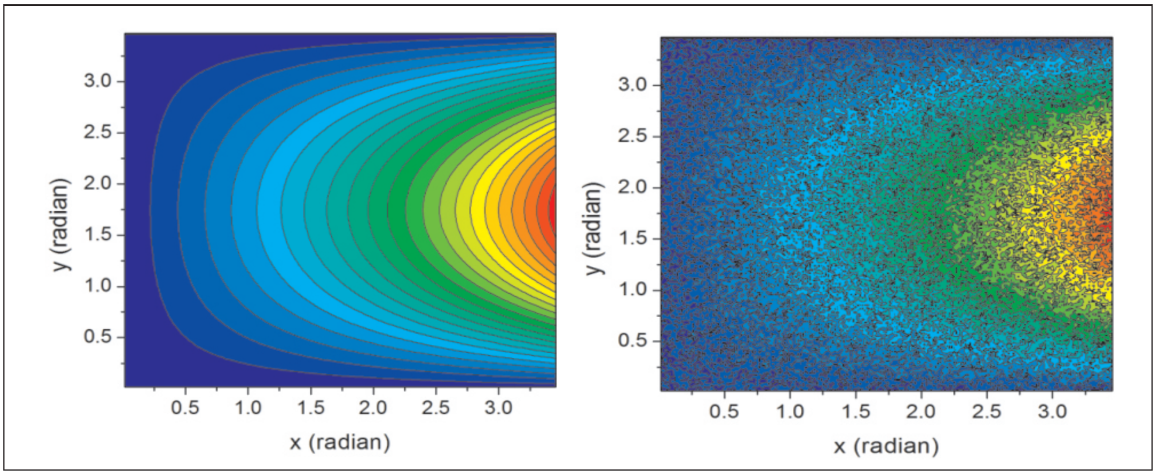
Eq. (6) holds only if the domain S does not contain a singularity. But if it has any singularity inside, the contour integral have a non-zero value. The singularity may be a discontinuity like crack or heat source. This property of holomorphic function is the basic concept to select the singularity which is a crack in this work.

Numerical simulation for detection of artificial crack

In order to investigate the characteristics of Eq.(6) in a two-dimensional plate, westartwith a simplest solution to Laplace equation in 2-D, which is,

$$T(x,y) = \mathbf{sin}\, y \,.\, s\mathbf{inh}\, x \tag{7}$$

This temperature field depicted in Fig. 2(a) naturally satisfies Eq. (6). Now an artificial random noise signal is added to the temperature field in Eq. (7) to simulate emissivity variance of surface in experiment, which is represented in Fig 2(b). The maximum value of random noise is set to the median of .



(a) (b)

Fig.2: Temperature distribution of (a) $T(x,y) = \mathbf{sin}\, y \,.\, s\mathbf{inh}\, x$ **, (b) noise-corrupted** $T(x,y)$**,**

An integral image obtained by calculating Eq. (6) at every point of uncorrupted image in Fig. 2(a) is represented in trimetric view in Fig. 3(a), where the integral values are very small(approximately zero) at all point (x, y) in the plate because it has no singularity. The corrup ted temperature distribution in Fig. 2(b) processed in the same manner using Eq. (6) is shown in Fig. 3(b). Its plan view is plottedagain in Fig. 3(c) to show a random distribution of integral value over the region due to random noise without any particular pattern or tendency.

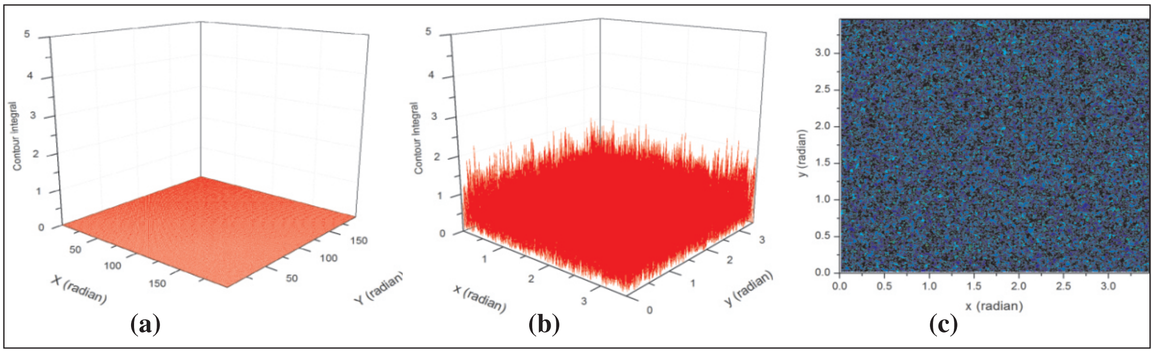
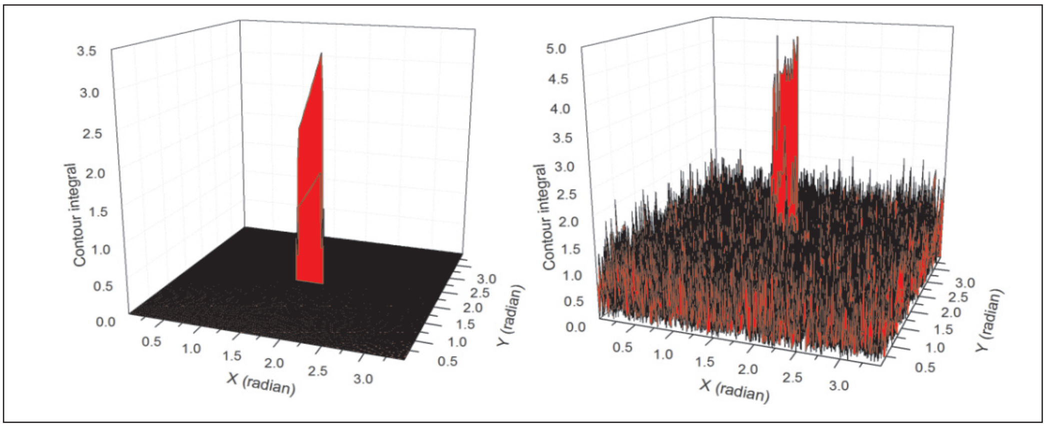
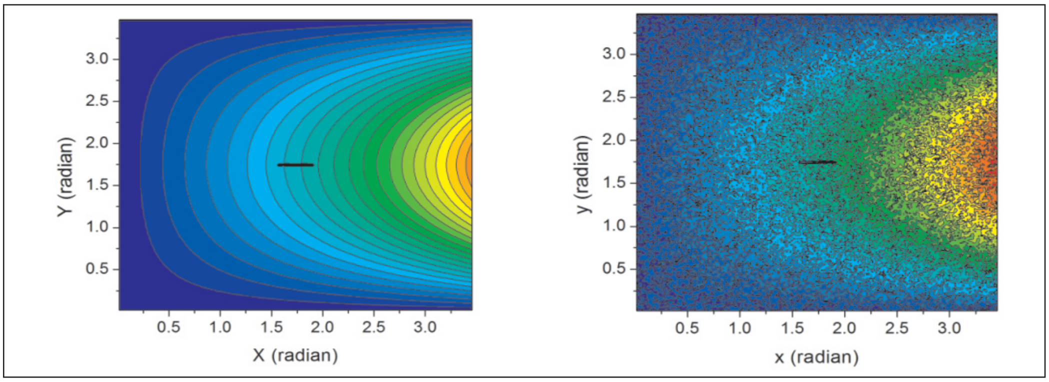


Fig. 3: Contour integral of (a) temperature field $T(x,y) = \sin y \,.\, \sinh x$, (b) noise-corrupted $T(x,y)$, (c) the plan view of (b)



(a) (b)

Fig. 4: A singular crack imbedded in (a) a field $T(x,y) = \sin y \,.\, \sinh x$, (b) noise-corrupted $T(x,y)$



(a) (b)

Fig. 5: Contour integral of (a) temperature field $T(x,y)$, (b) noise-corrupted $T(x,y)$

Now a slit of singularity is imbedded in the temperature field of Fig. 2 to simulate an effect of crack in a plate on the integral of Eq. (6) as shown in Fig. 4. Fig. 4(a) is the temperature distribution of a plate with no noise, and Fig. 5(b) is of a plate with the same noise as in Fig. 4(b). The same integral calculations over the temperature image as in Fig. 4 are performed and represented in Fig. 5, where the singular area (crack) is clearly seen. From these figures, the contour integral given in Eq. (6) has selected the singularity very well as it suppresses the temperature variance due to heat conduction and noise.

Conclusions

A new thermal gradient method in infrared thermography is proposed to detect surface crack in a thin plate using Cauchy-Riemann conditions of steady-state thermal field. A potential function, which is the conjugate harmonic function of temperature field, is derived and proved that its contour integral becomes zero over a domain where there does not exist any singularity. If the domain has any singular points like crack, the contour integral gives non-zero value, by which a crack in plate can be detected. A 2-D simple model for steady-state heat conduction is used to estimate by numerical analysis the performance of crack detection based on the method introduced in the paper. The temperature field of the model severely corrupted by random noise is integrated at each point of the temperature image along a closed loop. The integral image results in a good enhancement in image contrast because the contour integral reduces not only the variation of temperature produced by heat flow, but also the level of noise. In order to investigate how the integral image works with a singularity, an artificial singular slit like crack is put inside the plate model. After the temperature field containing both crack-like slit and noise is processed in the same way, the numerical simulation shows that the singularity is selected excellently through this method even when a high level of noise is present.

Acknowledgments

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