Detection of crack in metal plate by thermo sonic wave based detection using FEM

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Abstract— Non-destructive testing methods are commonly used for assessing various aircraft structural and engine components defects. Several types of NDT methods are being used for this purpose. One of the most advanced methods is thermography. Investigations have been made using transient ultrasonic heating to produce thermal signature of hidden flaws in an idealized structural component. Ultrasonic horn has been used as a thermal energy source in this method. In this paper Finite element method has been applied for studying the phenomenon of transient heat transfer in the component during NDT process. The preprocessing and analysis has been done using COMSOL package. Several iterations had been carried out for different boundary conditions and crack parametric variations viz. size and orientation.

Keywords— Transient heat transfer, Crack detection, Finite element analysis, FEA

I. INTRODUCTION

A large amount of research work has been conducted using various NDT & E techniques in the detection and identification of defects in both real and/or simulated aircraft parts. Transient thermography is one of the latest NDT & E techniques in development for effective use in the assessment of aircraft materials. It is a non-contact technique where the investigated area-material is heated or cooled by an external source (flash lamps, air gun, etc.) and the resulting thermal transient at the surface is monitored using an infrared camera. Since transient thermography is a high-speed, portable, non-contact and large area inspection technique, it has great potential for wide variety applications. [1]

Active Thermography (AT) is defined as applying a stimulus to a target to cause the target to heat or cool in such a way as to allow characteristics of the target to be observed when viewed by thermal imagery. These observed characteristics may be flaws sought in Non Destructive Testing (NDT) or norms sought in quality control. What separates active from passive thermography is the intentional application of heating, chilling or stress (active) that results in a temperature rise or fall in a target, as compared to an otherwise in situ (passive) target.

Depending on the external stimulus, different approaches of active thermography have been developed viz, Pulse thermography, Step heating, Lock-in thermography, Vibrothermography.

A. Vibrothermography(VT)

Vibrothermography is an active IR thermography technique where, under the effect of mechanical vibrations induced externally to the structure at a few fixed frequencies (based on the availability of commercial equipment), heat is released by friction precisely at defect locations (such as cracks and delamination). In such experiments, direct conversion from mechanical to thermal energy occurs and flaws are excited at specific mechanical resonances: local sub plates formed from delamination presence resonate independently of the rest of the structure at particular frequencies). Consequently, by changing (increasing or decreasing) the mechanical excitation frequency, local thermal gradients may appear or disappear. However, in current practice, fixed frequency excitation is commonly used, largely as a matter of
convenience and commercial availability. Finite element modelling applying three dimensional equations of linear elasticity permits evaluation of local energy concentration for components submitted to mechanical loading. For instance such study reveals that thermal patterns corresponding to two simulated delamination (10 x 7 mm and 7 x 7 mm) embedded in the specimen appear only with mechanical excitation between 13.5 and 15.0 KHz (specimen: 28 x 13 cm graphite epoxy beam with plies 90/0/90 attached to a piezoelectric shaker from one side).

Vibrothermography most significant advantages are: detection of flaws hardly visible by other IR thermography schemes (such as for instance closed cracks in gears) and inspection of large structural areas in situ. On the other hand, the required mechanical loading may be difficult to achieve.

\[
\begin{align*}
\rho C_p T_{x} + K T_{x} &= \beta \sigma \varepsilon - \alpha E T_{x} \varepsilon \\
\frac{1}{t} \left( \int_0^t \int_0^\infty \left\{ \sigma \right\}^T \varepsilon \, dx \, dy \, dz \, dt \right) &\cdots 2
\end{align*}
\]

Where \( T \) is the absolute temperature and \( \sigma, \varepsilon, \varepsilon_p \) are the components of stress, elastic strain and plastic strain respectively viewed as a function of co-ordinate \( x \) and time \( t \). The material constants \( \rho, C_p, K, \alpha \) and \( E \) are mass density, specific heat, thermal conductivity, thermal expansion co-efficient and Young’s modulus respectively. The statement of energy balance may be viewed as an equation governing the evolution of the temperature field.

Therefore in this paper an attempt to develop the FEM based methodology for thermosonic wave based detection of cracks in metal plates and crack sensitivity analysis has been carried out.

II. PROBLEM STATEMENT

A. Finite Element Modelling

For the purpose of analyzing the energy dissipation due to damages in an ultrasonically excited infrared thermography, simple plate geometry is been modeled and analyzed using COMSOL Multiphysics 4.1. Time dependent analysis has been carried out for dimensional plate geometry using the solid mechanics and heat transfer modulus of COMSOL Multiphysics. Tetrahedral elements have been used for meshing the plate geometry. The number of elements and size of the elements in the given geometry is defined by the convergence graphs. Ultrasonic thermography is basically a transient coupled thermo-structural study. Therefore convergence has been developed for three different cases based on the results of all three convergence graphs; number of elements in the plate is fixed. The three cases of convergence are convergence in strain energy for the plate geometry without crack; the second case is convergence in strain energy for insulated plate geometry with crack, where the plate is fully insulated and only heat generation will be induced due to ultrasonic wave propagation. And the third case is convergence in strain energy for plate geometry with crack having radiative and convective boundary conditions. Since the problem defined is a dynamic time dependent study, time average strain energy is been considered for the convergence study. Dynamic time average strain energy is given by

\[
\frac{1}{t} \left( \int_0^t \int_0^\infty \left\{ \sigma \right\}^T \varepsilon \, dx \, dy \, dz \, dt \right) \cdots 2
\]

Where \( \left\{ \sigma \right\}^T \) is the stress tensor, \( \varepsilon \) is the strain vector and \( t \) is the total time of simulation. Fig. 2 shows the meshed plate geometry used for the analysis. Fig. 3 shows the element distribution and boundary layer around the crack.

![Fig. 1 Typical Block Diagram for Lock-in Thermography](image-url)
Tetrahedral with quadratic shape order element type having maximum and minimum element size of 4.5mm and 0.508mm with 25348 elements has been used. A typical titanium material has been used and the governing equations considered are,

\[ \rho \frac{\partial^2 u}{\partial t^2} - \nabla \sigma = F \]  \hspace{1cm} \text{--------- 3}

Where \( \rho \) is the material density, \( t \) is the time, \( u \) is the displacement and \( F \) is the force,

\[ \delta_t \rho C_p \frac{\partial T}{\partial t} + \nabla ( -kVT) = Q \]  \hspace{1cm} \text{--------- 4}

This is the thermal governing equation used in model. Where \( \delta_t \) is the time scaling factor, \( C_p \) is the specific heat at constant pressure, \( k \) is the thermal conductivity, \( T \) is the absolute temperature and \( Q \) is the total heat generation.

\[ \delta_t \rho C_p \frac{\partial T}{\partial t} + \nabla ( -kVT) = \left[ \frac{\partial \rho C_p \ln \left( \frac{T}{T_0} \right) + \alpha E [\dot{\varepsilon} - \alpha (T - T_0)]}{\partial t} \right] \]  \hspace{1cm} \text{--------- 5}

The above equation is the thermo-structural coupled governing equation. Where \( T_0 \) is the initial temperature and heat generation in the model which is a function of strain rate.

B. Loads and Boundary conditions

The above Fig. 4 shows the loads and boundary conditions taken for the FEM analysis. The plate is fixed at one end and at the other end ultrasonic excitation is given. The ultrasonic excitation is given in the form of displacement at the horn contact region. Ultrasonic displacement is having peak amplitude of 20 µm and a frequency of 20 KHz. The total time of excitation is 1000 µsec. At the crack surface a contact pair having a friction co-efficient of 0.35 [6] has been defined. Free convective cooling is been given on all surface. Heat transfer co-efficient for free convection is 10 w/(m² K) [7]. A surface to ambient radiation has been defined at the top surface where the crack is present. The emissivity of the surface is taken as 1; this can be achieved in experimental process by coating the top surface with black paint. This is done mainly to enhance the thermal sensitivity. As the ultrasonic wave propagates in to the material it induces friction at the crack surface which results in heat generation. This has been introduced in the model in the form of heat generation equation. The governing equation for heat generation in vibrothermography is given below.

\[ \frac{\partial T_{xx}}{\partial t} + KT_{xx} = \beta \sigma \varepsilon^p - \alpha E T_{xx} \dot{\varepsilon}^e \]  \hspace{1cm} \text{--------- 6}

Where \( T \) is the absolute temperature and \( \sigma, \varepsilon^p, \dot{\varepsilon}^e \) are the components of stress, elastic strain and plastic strain respectively viewed as a function of co-ordinate \( x \) and time \( t \). The material constants \( \rho, C_p, K, \alpha \) and \( E \) are mass density, specific heat, thermal conductivity, thermal expansion co-efficient and Young’s modulus respectively. Assuming that the plastic work is not important and ignoring the materials micro structural effects the heat generation equation is given by

\[ Q = -\alpha E (T - T_0) \dot{\varepsilon} \]  \hspace{1cm} \text{--------- 7}

Where \( \delta_t \) is the time scaling factor. Including the entropy effect in the heat generation, equation is modified as
\[ Q = T \left( \frac{\partial S}{\partial t} + \alpha E(T - T_0) \right) \] ......... 8

Where,

\[ S = \rho C_p \ln \left( \frac{T}{T_0} \right) + S_{\text{elastic}} \]

\[ S_{\text{elastic}} = \alpha E \left( \varepsilon - \alpha (T - T_0) \right) \] ......... 9

Therefore the total heat generation equation used in the model is given by

\[ Q = T \left( \frac{\partial S}{\partial t} + \alpha E(T - T_0) \right) \] ...

Two types of contact forces are been induced in the model due to the displacement caused by the ultrasonic excitation. They are normal contact force and tangential contact force which are given as,

\[ f_n = p_n - K_p \Delta u \quad \text{for} \quad \Delta u \leq 0 \]

\[ f_n = p_n e^{\left( \frac{K_p}{p_n} \right) \Delta u} \quad \text{for} \quad \Delta u > 0 \] ......... 11

Where \( \Delta u \) is the relative displacement between the crack faces, \( f_n \) is the normal contact force, \( p_n \) is the contact pressure estimation at \( \Delta u = 0 \) and \( K_p \) is the penalty stiffness and tangential force as,

\[ f_t = K_t u_t \quad \text{if} \quad K_t u_t \leq \mu f_n \quad \text{Stick Condition} \]

\[ f_t = \mu f_n \quad \text{if} \quad K_t u_t > \mu f_n \quad \text{Slip Condition} \] ......... 12

Where \( f_t \) is the friction in tangential direction, \( u_t \) is the displacement in tangential direction, \( \mu \) is friction coefficient and \( K_t \) is the high spring stiffness resulting in small deformation during stick.

III. RESULTS AND DISCUSSION

The focus lies on their velocity and temperature waveform, to understand the vibration pattern along the crack and temperature rise due to heat generation caused by ultrasonic excitation.

Four different points in the plate geometry were chosen shown in figure. These points are on the top surface on the plate. Where A is the point at the horn interface and the point at which wave starts propagating into the material point B is at distance of 31.75 mm from the horn interface, which is one forth the length of the plate. Point C is at a distance of 63.4 mm from point A, which is near the half the length of the plate. Point D is at a distance of 95.25 mm from the point A, which is three fourth of the plate length. At these points particle velocity and has been analyzed to see the ultrasonic response of the plate geometry without crack and with crack and also the temperature distribution and velocity variation with time step for the two different boundary conditions viz. insulated and convective and radiative boundary condition also has been analyzed. Previously a convergence study so has been conducted based on convergence rate of strain energy with respect to no of elements also has been carried out. The variations in particle velocity and temperature distribution are plotted based on time step and frequency as shown in Fig. 5 to 13.
In-plane longitudinal velocity at various different points in the plate geometry with crack having insulated boundary condition is as shown in Fig. 8. Delay in velocity time history as the wave propagates in the plate can be observed. At point B there is a delay of 1 µsec, at point C there is a delay of 5 µsec and at point D there is 12 µsec delay. Increase in the velocity amplitude is seen due to the presence of crack.

In-plane longitudinal velocity at various different points in the plate geometry with crack having convective and radiative boundary condition is as shown in figure 9. Delay in velocity time history as the wave propagates in the plate can be observed. At point B there is a delay of 1 µsec, at point C there is a delay of 5 µsec and at point D there is 12 µsec delay. Increase in the velocity amplitude is seen due to the presence of crack. The average velocity and average temperature for plate geometry without crack is as shown in Fig. 10. As there is no crack present in plate, there will be no heat generation. Therefore in Fig. 10 there is no variation in temperature. Where as the average velocity is also less compared to plate geometry with crack.

The average velocity and average temperature for plate geometry with crack having insulated boundary conditions is as shown in Fig. 11. Due to the presence of crack there is heat generation in the crack surface, which can be seen from the temperature variation in Fig. 11. Since the plate is fully insulated there is higher temperature gradients compared to plate geometry with convective and radiative boundary conditions.

The average velocity and average temperature for plate geometry with crack having convective and radiative boundary conditions is as shown in Fig. 12. The velocity is higher than the velocity in the plate without crack, and the temperature around the crack is increasing which shows the presence of crack. As time progresses the average temperature around the crack location is been stabilized.
The temperature distribution in the plate geometry is shown in Fig. 13. The temperature rise near the crack can be seen in the zoomed part. From the Fig. 13 it can be seen that the temperature is increasing only at the crack and at all other positions of the crack is at ambient temperature.

IV. CONCLUSIONS

Finite element method technique for thermosonic wave based detection of cracks in metal plate has been developed. The presence of crack has been identified through variation in the velocity and rise in temperature around the crack. The velocity range that was achieved in this simulation is matching with the theoretical formulation of Rayleigh-Lamb frequency equation.

It is very clear from the analysis that the presence of crack shows a deviation of velocity profile and temperature profile with respect to time step from the normal profiles obtained for the case of plate without crack. Thus it is possible to analyze the vibrothermographic technique based NDT method of crack detection through FEM and there by reducing the efforts put in experimental testing in terms of money and material and thus reducing the lead time.

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