TLM modelling of heat flow through defects in aircraft sandwich structures

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Abstract

The Transmission Line Matrix (TLM) model is applied to describe heat flow in highly inhomogeneous materials such as aircraft sandwich structures. The medium investigated, in which an electromagnetic wave propagates, is treated as an electric circuit. The resultant amplitude of pulses after introducing them into the transmission-line circuit is determined. The application of the model has enabled us to reveal the temperature field distribution in sandwich structures being heated by an external source. Special attention was focussed on the neighbourhood of such defects.

Introduction

Hitherto methods for analytic and numerical solving of heat flow equation in solids (e.g.finite-difference methods) are inconvenient, complicated and burdened with computation instability problems. Due to the formal similarity of the heat flow equation and the telegraph equation, the TLM method can be successfully applied to the problems of diffuse heat propagation in the three-dimensional space [1- 6]. The advantage of the TLM method is the ease of setting of various boundary conditions, e.g. constant temperature difference, constant heat flux, ideal thermal contact and ideal thermal isolation. Numerous papers [7 - 12] present examples of the application of TLM to the analysis of heat transfer. Gui, Webb and Gao used this numerical method to describe heat flow in semiconductor devices [7]. Henini and de Cogan simulated heat flow during the technological process of soldering of semiconductor devices [8]. The problem of application of the transmission line model in the case of a line with losses was reported in 1977 at the conference "Progress in Applied Computational Electromagnetics" [9,10]. The problem of heat flow in inhomogeneous structures, taking as a example conductivities, was the subject of interest of Malachowski and de Cogan [11].

This paper proposes a method for simulation of heat-flow in aircraft composite sandwich structures which exhibit their defects during aircraft usage, e.g. delamination, disbanding, lack of stiffness, water ingress. During the production of composite materials, other defects can also occur, e.g., porosity or voids, inclusions or incorrect fibre direction [13]. One method for detection of these defects is the thermographic method, consisting of thermal excitation of material, and then remote

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and contactless assessment of the temperature distribution of the body being investigated. Thus it is necessary to have a simple and precise description of heat transfer in such materials in the presence of defects.

The idea of the transmission line model

The essence of the transmission line model consists in the fact that the medium in which an electromagnetic wave propagates can be treated as an electronic circuit composed of many simple elements: resistances, capacitances, and inductances. Next, the reaction of such a line to temporal variations of, e.g., the pulse rise at the end of the line is investigated. In a one-dimensional lossy transmission line (being appropriate for modelling thermal effects) the pulse potential can be described as:

$$\frac{\partial^2 \phi}{\partial x^2} = L_d C_d \frac{\partial^2 \phi}{\partial t^2} + R_d C_d \frac{\partial \phi}{\partial t} \tag{1}$$

where: ϕ is the potential

x is a coordinate

L_d is the inductance per length unit of the line

C_d is the capacitance per length unit of the line

R_d is the resistance of the line length unit.

t is the time,

Due to the application of the method for analysis of transmission line to the problems of heat flow, it is assumed that only the lines of low inductances and capacitances but of high losses are being investigated. Hence, the second derivative over time is neglected in Eq. (1).

Assuming the analogy between temperature and electric potential, the TLM model has been applied to the equation of heat diffusion in aircraft sandwich structures.

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho C_p}{k_T} \frac{\partial T}{\partial t} \tag{2}$$

assuming that $R_d C_d = \frac{\rho\, C_p}{k_T} \geq \frac{\Delta t^2}{\Delta x^2}$

where: T is temperature

ρ is the medium density

C_p is its specific heat

k_T is the thermal conductivity

Δx is the spatial discretisation in the x-axis direction

Δt is the temporal discretisation

In the TLM method, we consider the solving of the circuits by taking into account propagation of pulses of the delta-function of Dirac shape along transmission lines which, in the one-dimensional case, are parallel and lie in the signal propagation direction. After introducing pulses into the network of discretised elements (nodes), their cumulative magnitude at any point at subsequent times (which depends on several factors, including dispersion) is monitored

All the lines in the network are characterised by the same delay time *Δt*, hence all the pulses arrive at nodes simultaneously. The mechanism of pulse propagation in the one-dimensional case is illustrated in Fig. 1.

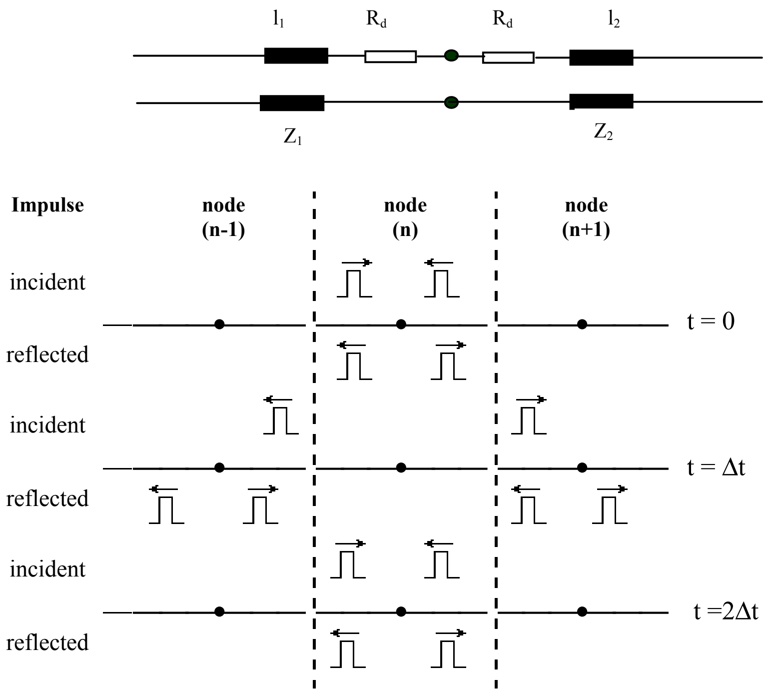

Fig. 1. Scheme of propagation of pulses along one-dimensional transmission line

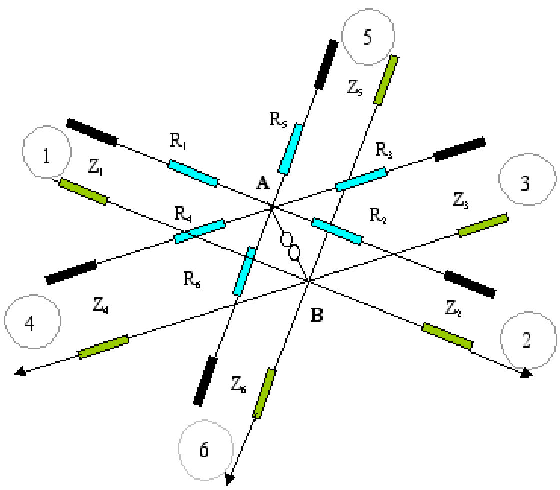

Fig. 2. Three-dimensional model of transmission line

In the three-dimensional case (being the one we deal with in the analysis of heat flow in sandwich structures), the least discrete element of the solid in respect of electric parameters can be presented by a set of transmission lines (Fig. 2), where the 1 and 2 direction overlaps the *x* axis, 3 and 4 direction overlaps the *y* axis, and 5 and 6 direction overlaps the *z* axis. The current generator *AB* models heat generation in each element investigated, and the cells containing resistors *R* connected by means of a capacitive lossless transmission line Z model the thermal resistance and thermal capacitance, respectively.

If a narrow pulse of potential (temperature jump) is introduced into such a circuit, it will propagate in the three-dimensional medium and its direction and sense of propagation can be described with the numbers 1 to 6. The pulses propagating will be dispersed on the nodes of electronic elements. Next, the pulses dispersed combine creating the resultant pulse in the node. This pulse is a local solution of equation:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = R_d C_d \frac{\partial \phi}{\partial t} \tag{3}$$

Thanks to the TLM method, one can determine the height of pulses after introducing them to the circuit of the three-dimensional transmission line. The capacitance of a three-dimensional node can be divided into three transmission lines in each rectangular prism of dimensions Δx, Δy and Δz. The pulses introduced to the circuit incident on the node undergo scattering.

The possibility of pulse reflection occurs also on inter-nodal impedance discontinuities. Such a case takes place in inhomogeneous materials when the following dependence is fulfilled in adjacent regions: $R_{di}C_{di}=R_{di+1}C_{di+1}$. The height of pulses inciding at the moment $(k+1)\Delta t$ can be calculated from the relation:

$$_{k+1}V_j^i(x,y,z) = \Gamma_{j\,k}V_j^s(x,y,z) + (1-\Gamma_j)_k V_j^s(u,v,w) \tag{4}$$

where the respectively of pulse in direction j=1, 2,...6 can be calculated from:

$$\Gamma_j = \frac{Z(u,v,w) - Z(x,y,z)}{Z(u,v,w) + Z(x,y,z)} \tag{5}$$

Considering all conditions mentioned above one obtains the time-dependent temperature variation in each node of the three-dimensional space. The above method for description of the temperature field distribution has been used to analyse the heat flow in aircraft sandwich structures. Such defects, which can appear during routine operation, could affect the in-flight safety of the aircraft [14].

Results of investigation

The numerical method described above has been applied to the temporal analysis of temperature distribution in a sandwich structure in which the facing layer of 1 mm in thickness is made of glass-epoxide composite, while the core of 8 mm in thickness is a polyurethane foam. The following cases have been considered:

1. a layer of air of 1 mm in thickness is introduced over some region between the facing layer and the core, illustrating disbonding of the material (one of the most dangerous defects noticed in this type of structures);

2. a layer of water of 1 mm in thickness is introduced over some region between the facing layer and the core;

3. another material (aluminium foil of 0,3.mm in thickness) is introduced between the facing layer and core, illustrating an inclusion.

The division of the sample investigated into individual nodes is presented in Fig. 3. The cell dimension have be taken in the plane parallel to the surface as Δx = 1 cm, Δy = 1 cm and in the direction perpendicular to the surface as Δz = 1 mm. The surface of the cladding has been heated to temperature 40°C. It has been assumed that the bottom surface of structure has constant temperature of 10°C.The computation has been performed for a 12-second interval with the step Δt = 0,05 s. Thermal properties of the materials investigated taken to computation are presented in table 1.

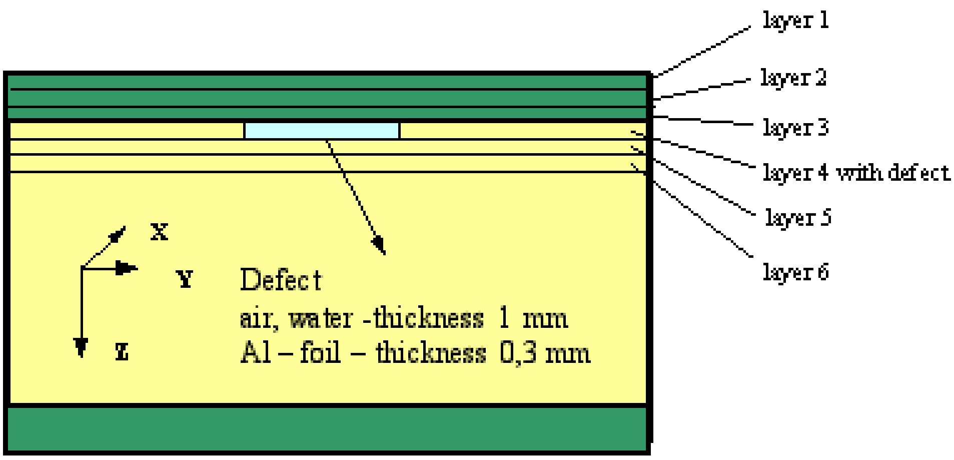

Fig. 3. Division into nodes of aircraft sandwich structure made from facing (epoxide composite) and core (polyurethane foam).

TABLE 1

Material	**Density** ρ [g/cm^3]	**Specific heat** C_p [J/gK]	**Conductivity of heat** k [W/cmK]	**Thickness** z [mm]
Composite	2	0.85	0.0056	1
Foam	0.06	1.25	0.00027	8
Air	0.0012	0.92	0.00084	1
Water	1	4.18	0.00596	1
Aluminium	2.7	0.922	2.3	0.3

The example of temperature variations in the direction perpendicular to the surface of the material investigated is illustrated in Fig. 4. On the other hand temperature variations in the layers being investigated for various defects are presented in Fig. 5. The results of computations reveal that two upper layers of the facing (1, 2) are heated almost evenly.

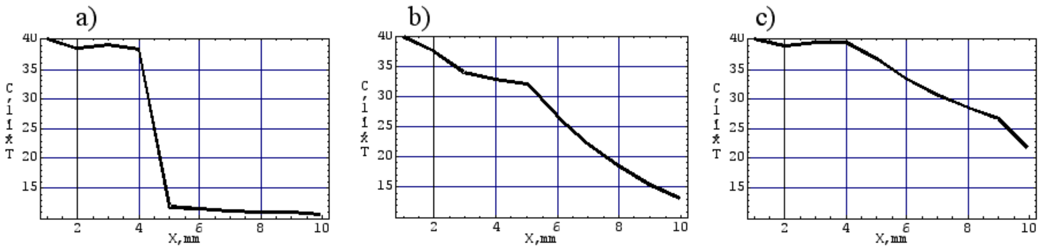

Fig. 4. Temperature distribution, T(x,y,z), in successive layers of aircraft sandwich structure after 12 s: a) sample with air; b) sample with water; c) sample with aluminium foil

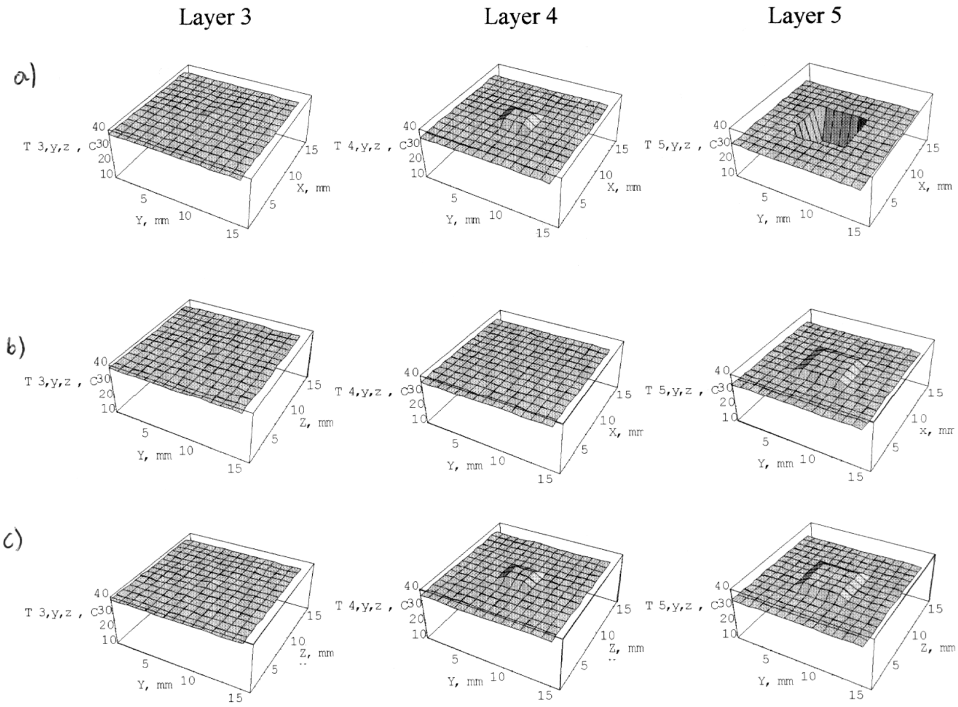

Fig. 5. Temperature distribution, T(x,y,z), in layers 3, 4 and 5 of aircraft sandwich structure with different defects after 12 s: a) sample with air; b) sample with water; c) sample with aluminium foil

In all investigated cases, in the layer direct over the defect (layer 3) and in the defect (layer 4) and in layer under the defect (layer 5), the temperature was different. The direction of change of the temperature depends on the defect's thermal properties. In the case when the defect is the air bubble the temperature in layer 3 and 4 is heightened but in layer 5 is reduced. When the defect is water, the temperature of layer 3 is reduced but temperature of layer 4 and 5 is heightened. When the defect is aluminium the temperature in layer 3, 4 and 5 is heightened.

Conclusion

The aircraft composite sandwich structures under investigation are inhomogeneous materials. They are characterised by regions of abruptly varying thermal parameters. Conventional analyses of thermal variations occurring in these structures under the influence of a heat pulse are most often insufficient here. The TLM numerical method proposed for spatial-temporal analysis of the problems of heat flow enables one to assess quickly the actual thermal changes in aircraft composite sandwich structures.

The results obtained have revealed that, in the initial period of heating, considerable temperature differences occur in the disbanding region or in the presence of water or aluminium and in the layers adjacent to the defect. Therefore, it seems to be advisable to investigate further the time after which the differences in temperature distribution will being to vanish, as well as to investigate the temperature variations in the layers more and more distant from the defect. Interesting problem will be investigated TLM modelling of heat flow in aircraft sandwich structures with honey comb core.

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