Journal of Thermophysics and Heat Transfer
Vol. 7, No. 4, Oct.–Dec. 1993

Three-Dimensional Thermal Analysis for Laser-Structural Interactions

Hartmut H. Legner,* Albert W. Bailey,† and Michael F. Hinds‡
Physical Sciences, Inc., Andover, Massachusetts 01810

Abstract

A THREE-DIMENSIONAL thermal analysis method with direct application to laser-structural interactions has been developed. This robust, implicit finite-volume technique solves the enthalpic form of the heat conduction equation for laser radiation interacting with three-dimensional aerospace structures. It utilizes finite elements derived from the structural analysis and accommodates arbitrary beam profiles to compute the ablative material response. Computed results for a composite hat-stiffened panel are illustrated. This method has also treated laser-structural problems involving oblique beam incidence, complex structures, multiple materials, and beam slewing.

Contents

The vulnerability of aerospace structures to laser radiation depends upon the structural material response under thermal loads. The thermal loads on the vehicle consist of laser energy absorption and energy fluxes produced by the aerothermodynamic environment including external aerodynamic heating as well as internal heat transfer associated with structural cooling and cryogenic fuels. This synoptic emphasies the thermal damage of such structures to laser radiation. The structural part of the laser-structural interaction problem is not considered herein. The stress fields are modified by the elevated temperatures and loss of mass (structure) that the absorbed laser energy produces. This structural behavior can be analyzed using a component of a unique integrated analysis method entitled vulnerability analysis of aerospace structures exposed to lasers (VAASEL).[1–4] This new code consists of a threat analysis to determine the incident radiation on the target, a nonlinear, time-dependent, thermal analysis to determine the thermal response of the target, a material and geometric nonlinear structure analysis to determine structural response, and a failure analysis to determine strength and stiffness degradation. The three-dimensional thermal analysis capability of VAASEL is highlighted in this synoptic.

Three-dimensional thermal analysis is necessary for laser beams striking geometrically complex structural surfaces such as a wing-fuselage juncture at an angle of incidence to both components. Up to this time, no extensive analysis capability existed to treat such a laser-material interaction. Even though previous approaches to the thermal problem[5] had full three-dimensional capability, they lacked the geometrical flexibility needed for general aircraft or aerospace vehicle configurations. Consequently, the thermal model consists of three major parts: 1) geometry submodule, 2) laser ray specifications, and 3) the finite-volume methodology.

We first consider the structural geometry. For the thermal analysis, the structural elements are categorized as being either four-node quadrilateral surface elements or eight-node solid elements. A surface element has at least one face exposed to a nonstructural environment; an interior solid element is wholly surrounded by other structural elements. Once this level of distinction has been made, then all the metric information associated with the elements such as grid locations, surface area, volume, etc., can be determined.

The definition of the beam geometry is very important. Let us imagine that the center of the beam strikes one particular surface element at a known position. Neighboring beam "rays" strike nearby. In order to perform accurate simulations of the beam-target interactions, it is necessary to follow each ray as it propagates through the structure. This would not be very important if only a top surface of elements were intercepted by the beam, however, if elements are removed due to ablation during the engagement, then the beam interactions with the subsequent elements must also be known a priori. As such, the laser spot is divided up into a number of rays with individual power levels and path information associated with each ray. These rays can be defined once the spot location and size are provided. This procedure has been fully automated. Once an aim-point is specified, a random distribution of neighboring rays is selected to provide adequate exposure of all surface and subsurface elements.

The three-dimensional thermal analysis method uses a modified version of the multidimensional ablation code used extensively[5] and proven to perform accurately and reliably. This is a finite-volume code with a conservative formulation which maintains integrated energy. Since its uses a fixed grid structure, some zones become empty as material ablates. It is first-order accurate in time and second-order accurate in space with uniformly spaced grids; with nonuniform grids (which may be required for complex geometries) the results become first-order accurate in space as well. A fully coupled, fully implicit scheme using a sparse matrix solution is used for the thermal diffusion simulation. This is done to insure the proper performance of the method under the most adverse circumstances.

The change in the thermal energy of a general three-dimensional element is given by the following equation:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \underbrace{-\text{VOLUME}\,[\nabla\cdot(\bar{k}\cdot\nabla T)]}_{\text{Transfer Term}} + \text{AREA} \times \underbrace{\left[\underbrace{-e\sigma T^4}_{\text{Radiation}} \underbrace{- HAe^{-T_{\text{Ablation}}/T}}_{\text{Ablation}} + \underbrace{\alpha\cdot I}_{\text{Laser}} + \underbrace{S_{\text{other}}}_{\text{Other}}\right]}_{\text{Source (Sink Terms)}} \quad (1)$$

where energy changes occur due to either transfer into (out of) the element or energy source (sink) terms within the element. A more detailed description of the equations used in the three-dimensional thermal analysis method is provided elsewhere.[6,7]

Presented in part as Paper 91-1508 at the AIAA 22nd Fluid Dynamics, Plasma Dynamics, and Lasers Conference, Honolulu, HI, June 24–26, 1991; received Dec. 4, 1991; synoptic received March 16, 1992; accepted for publication March 17, 1992. Full paper available from AIAA Library, 555 West 57th St., New York, NY 10019.

*Principal Research Scientist. Associate Fellow AIAA.
†Principal Scientist. Member AIAA.
‡Senior Programmer.

The most complex three-dimensional thermal bench mark problem investigated laser interaction with a hat-stiffened panel. The problem involved the most grid elements (2574) and the most laser ray paths (6500) through the structure. The specification of the problem are given as inserts in the overall geometry of the graphite epoxy composite panel as shown in Fig. 1. The continuous laser (CW) laser beam strikes the flat portion of the panel at normal incidence with a 1.27-cm swath over the entire width of the panel. The incident beam has an intensity of 1 kW/cm^2. Even though the geometry is rather complex, there is an additional complication associated with the lay-up configurations of the plies. The variations in ply lay-ups lead to significant thermal conductivity variations for different parts of the structure. There are six different ply lay-ups identified.[7]

Prior to describing results of the calculation, the cross-sectional skeleton of the hat-stiffened panel is shown in Fig. 2. All of the grid elements in a plane are shown. There are 18 identical sections in-depth. A particularly interesting section is one that is near the middle of the panel (section no. 9).

In addition to the cross-sectional skeleton, Fig. 2 illustrates the grid elements ablated (or removed) from section 9 after 0.6 s of laser irradiation. The removed elements are shown with shading. Note that the skeleton has the correct number of elements but is *not* drawn to geometric scale. The entire lower panel elements have been ablated away, the sloping-stiffener elements have also lost some mass, and the upper section (which feels the normal incident beam) has already lost nearly one-half of its mass. After 1.0 s of laser radiation, most of the elements in the section have been removed, and after 1.4 s, only two elements remain. They have apparently received less absorbed radiation thus highlighting the importance of having a sufficient number of laser rays that reach all grid elements.

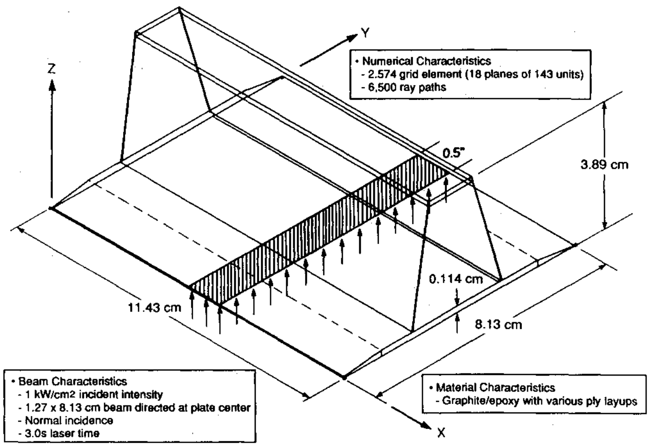

Fig. 1 Geometry of the composite panel.

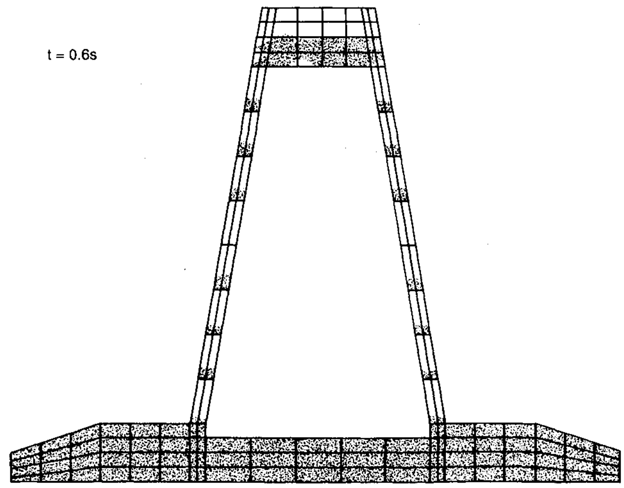

Fig. 2 Elements removed in Sec. 9 of the panel at 0.6 s.

The computational results[7] also revealed that the effect of the laser beam is relatively confined to only four of the 18 sections comprising the panel. Large thermal gradients are confined to these sections.

This example illustrates the very general range of applications that the three-dimensional method can analyze in the area of laser-structural interactions. It is useful, perhaps, to review the features that the method can currently handle. First of all, it is three-dimensional in all respects; i.e., the target geometry can be an arbitrary three-dimensional shape with internal passages and the beam can have an arbitrary incident power profile. Second, multiple materials can be employed with the individual materials characterized with general nonisotropic properties. Third, material removal by ablation is directly modeled once albation enthalpies and ablation temperature are known for the material. Fourth, very general boundary conditions permit surface radiation, surface heat transfer, and surface temperature to be specified. Fifth, the method is extremely robust with very limited opportunities for nonconvergence. The output of the three-dimensional thermal analysis solver is directly suited to further in-depth structural analysis. Specifically, the method can provide the temperature distribution as a function of position and time in the structure. It also provides the contour of the structure as the surface ablates. The ability to accomplish this in a three-dimensional fashion is an important triumph of the approach.

Acknowledgments

The work was sponsored by Northrop Corporation as part of their prime contract on VAASEL with the USAF Flight Dynamics Laboratory. Richard Blauvelt and Barry Megginson are the Principal Investigators and Jay N. Kudva is the Northrop Program Manager. Northrop developed the geometry submodule, the ray path subroutine, and the geometric definition of the analyzed structures. Don Paul, Chris Clay, V. B. Venkayya, and Estelle Anselmo provided direction from the Wright Laboratory.

References

[1]Kudva, J. N., Legner, H. H., Jacobson, M. J., Kamat, M. P., and Tossavainen, E. W., "Vulnerability Analysis of Aerospace Structures Exposed to High-Energy Lasers (VAASEL)," Northrop Corp., AFWAL TR-86-3052, Phase I Final Rept., Hawthorne, CA, Dec. 1986.

[2]Kudva, J., Jacobson, M., Legner, H., and Clay, C., "Development of an Integrated Computer Code for Laser Vulnerability Analysis of Aerospace Structures," Third DoD Conf. on Hardening of Tactical Flight Vehicle Structures Against Lasers, Wright-Patterson AFB, Dayton, OH, Aug. 26–28, 1986.

[3]Legner, H., Rigos, D., Bailey, W., Hinds, M., Modak, A., Blauvelt, R., Saether, E., Kudva, J., and Clay, C., "Thermo-Structural Laser Vulnerability Analysis," AIAA/DNA Laser Effects and Target Response Conf., Monterey, CA, March 15–18, 1988.

[4]Anselmo, E. R., and Kudva, J. N., "Thermal Structural Analysis Using VAASEL," First Thermal Structures Conf., Univ. of Virginia, Charlottesville, VA, Nov. 13–15, 1990.

[5]Bailey, A., and Modak, A., "Numerical Simulation of Laser Ablation with Cavity Reflections," *Journal of Thermophysics and Heat Transfer*, Jan. 1989, p. 42.

[6]Kudva, J. N., Saether, E. S., Blauvelt, R. E., Megginson, B. J., Hinds, M., Bailey, A., and Legner, H. H., "VAASEL Final Report," Vol. 3, *Theoretical Manual*, AFWAL-TR-90-3070, June 1991.

[7]Legner, H. H., Bailey, A. W., and Hinds, M. F., "Three-Dimensional Thermal Analysis for Laser-Structural Interactions," AIAA 22nd Fluid Dynamics, Plasma Dynamics and Lasers Conf., AIAA Paper 91-1508, Honolulu, HI, June 24–26, 1991.