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Integrating Thermal and Structural Analysis with Thermal Desktop™

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ABSTRACT

Structural and thermal engineers currently work independently of each other using unrelated tools, models, and methods. Without the ability to rapidly exchange design data and predicted performance, the achievement of the ideals of concurrent engineering is not possible.

Thermal codes have been unable to exploit the geometric information in structural models and the CAD design database, and do not facilitate transfer of temperature data to other discipline's analysis models. This paper discusses the key features in Thermal Desktop for supporting integrated thermal/structural analysis. Approaches to thermal modeling in an integrated analysis environment are discussed along with Thermal Desktop's data mapping algorithm for exporting temperature data on to structural model grid points.

INTRODUCTION

Tighter coupling between thermal and structural analysis has long been sought, but has been prevented by incompatibilities in existing tools. Each discipline makes abstractions in order to reduce the problem into one that is efficient for calculations on a computer, and that most clearly represents the physics being modeled. These different representations often make it difficult to transfer data from one model to another.

For example, a thermal model might consist of a geometric surface model for radiation calculations, and an arbitrary set of nodes and conductors for other portions of the model. A significant part of the model may not be represented by graphical entities, requiring data from the thermal model to be mapped to the structural model by hand, or by generating a custom program to map thermal nodal temperatures onto structural FEM nodes.

Changes in the design or in either of the analysis models usually renders the custom program invalid. Often one of the analysis models will be changed without the other engineers' knowledge, invalidating the data mapping. Shortcuts are sometimes taken in which a few temperatures are mapped to the structural model, and then the remaining temperatures computed by performing a steady state solution using the structural mesh. These approaches are laborious, time consuming, and prone to error, which may lead to artificial structural deflections.

Attempts have been made to use the radiation model geometry (TRASYS [1], TSS [2]) as a basis for automating the mapping of temperatures. A fundamental problem with such attempts is that the model is only concerned with the surfaces of the model that participate in radiation exchange. Temperature gradients within 3D solid regions are not represented, and are not available for interpolation. For example, predicting thermal distortion for optical systems requires analysis of many solid features such as the complex webbing and mounting structures on the back of mirrors, and the structures that support the optical components. The restriction of current radiation tools to use only conic surfaces with regular boundaries also creates significant differences in the structural and thermal representations, making interpolation difficult or, in some areas, impossible.

Using the geometry of the radiation model, temperatures may only be interpolated within individual surfaces at best. The radiation model does not contain rules for interpolating temperatures throughout the entire domain as does a finite element model (using the element's shape functions). The radiation model does not contain information on how temperatures vary from surface to surface. Temperatures must therefore be extrapolated to the edge of each radiation surface, ignoring any connectivity between them.

Another common but fundamentally flawed approach to integrating structural and thermal models is to use structural FEM codes for building thermal models. Codes based on these methods sometimes (but not always) recognize the fact the matrix of terms produced by FEM is fully compatible with SINDA/FLUINT, and that ad hoc generation of conduction and capacitance terms using element centroids can be avoided. Such finite difference centroid methods may introduce additional errors when returning temperatures to the structural program. For example, averaging element temperatures to produce nodal temperatures artificially smooths temperature variations, reducing the predicted structural displacements.

Yet even when centroid conversions and their associated problems are avoided, the resulting tools fail to gain widespread acceptance. Such simple approaches have been reinvented many times and have existed for years in various forms, and yet have failed to address the thermal/structural integration problem for a variety of reasons [3].

One reason for the failure of the FEM-translation approach is that if FE methods are used exclusively, they usually result in intractable thermal models due to excessive run times for radiation calculations. Even simplification of the structural model into a suitable thermal model typically results in prohibitive run times, the main reason being the fact that curved surfaces must be modeled using flat finite elements.

A spherical surface that can be modeled with a simple TRASYS surface subdivided into a few nodes must be modeled with many flat elements to maintain geometric fidelity. Often the thermal representation is grossly simplified; cylinders are converted into four sided tubes and spheres are simplified into boxes. Such simplifications may in some cases produce reasonable thermal results, but such vast differences in the geometric representation between the structural and thermal models make temperature mapping back onto the structural model extremely difficult. Brute-force mappings such as “nearest node” are often used, which produce artificial distortions.

Thus, current approaches have forced thermal engineers into two unpleasant choices. One, use a purely finite element based approach in order to aid in translating data from the thermal model to the structural model and suffer from excessive turn around times for analysis, or use present methods and suffer from excessive turn around times in the effort to translate data to the structural model. Both approaches slow the iterative process characteristic of integrated design and optimization in a multi-discipline environment, destroying the concurrency that is trying to be obtained.

THERMAL DESKTOP APPROACH

Thermal Desktop™ is a CAD-based geometric front-end to SINDA. It is a key part of the approach because its design overcomes many bottlenecks of thermal-structural design integration [4]. One such bottleneck is the accurate mapping of temperatures produced by SINDA back to similar, but not identical, structural models.

A unique resolution to the “model mapping problem” was developed and added to Thermal Desktop: interpolation information is taken directly from the thermal model, thereby eliminating the requirement for the thermal and structural models to be the same. This means that thermal models and structural models can be developed independently using modeling tools and methods honed for each specialty, while preserving the ability to pass accurate temperature data from the thermal analysis tool to the structural tool. This approach is consistent with the philosophy of the development of Thermal Desktop: the key to integrated design *that is acceptable to end users* is not to force the use of a single compromised tool, but rather to allow each specialty to work with their existing fully-featured tools and concepts while providing seamless pathways for exchanging data and for maintaining common design configurations.

Postprocessed data (temperatures, heat loads, etc.) calculated for a thermal model may be mapped to any set of arbitrary point locations. The thermal model may consist of TRASYS/TSS-like finite difference surfaces (cones, spheres, paraboloids, etc.), finite element primitives (triangles, quads, tetrahedrons, wedges, and bricks), and arbitrary nodes and conductors. For each point for which data is to be mapped (e.g., a NASTRAN grid point), Thermal Desktop checks each thermal object for proximity to the point. If the point lies on or in the object, data for the object is interpolated at the point location. The thickness assigned to surfaces for conductance/capacitance calculations is used to define the 3D space for which the surface occupies and includes the effect of surfaces with different nodes on each side.

Finite difference surfaces interpolate linearly in their parametric space (i.e. [angle, height] for a cylinder). Finite element primitives use their corresponding shape functions. True bilinear interpolation is done on quad elements; trilinear interpolation is done on brick elements. Maximum accuracy is obtained in mapping thermal data since the same functions used to define the temperature field in the thermal solution are used for interpolating data points.

To provide a generalized capability, locations for which thermal data is to be mapped may be input as an ASCII text file specifying a name (for example, a structural FEM node ID) and an [x,y,z] location. Output is generated as an ASCII file consisting of the name and the mapped thermal data at the location corresponding to the input name.

In addition, more automated integration with common structural analysis packages is provided. For example, locations to be mapped may also be specified using a NASTRAN input deck. Grid points are read directly from the input deck and temperature data is output in NASTRAN load set format.

DEMONSTRATION MODEL

A simplified optical telescope model is presented to demonstrate the end-to-end procedure for a combined thermal/structural analysis. The level of detail in the model is typical of a conceptual design model.

The model demonstrates the following key points:

- Efficient use of combined finite difference and finite element methods for the thermal model.
- Independent abstractions of the telescope for thermal and structural models.
- Interpolation of temperatures from thermal model to structural model.

STRUCTURAL MODEL DESCRIPTION

The telescope is representative of current remote sensing satellites with a 1 meter resolution capability. It is a 3 mirror, Casagrain telescope with a 28” diameter primary mirror.

The metering structure is an invar, stiffened shell which is 36” long and 30” in diameter. A 3-legged spider supports the secondary mirror assembly. The aft metering structure is a truss-like structure of invar, protected by a thermal enclosure. Overall, the structural model contains approximately 1000 grids and 1500 elements. Figure 1 depicts the telescope model, while Figure 2 shows a cut-away side view. There are 6 optical elements in the light path in the following order:

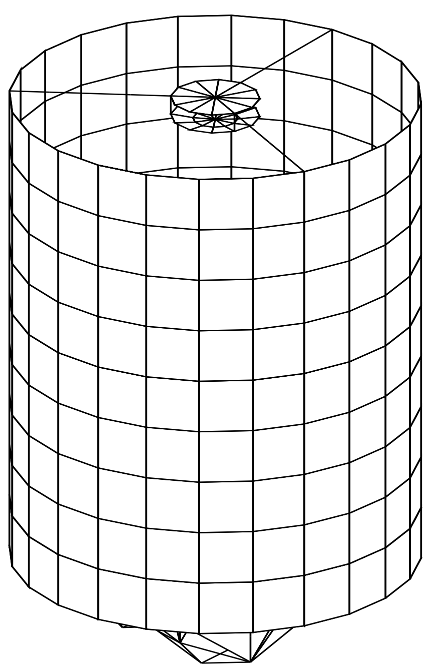

Figure 1: Demonstration Telescope Model

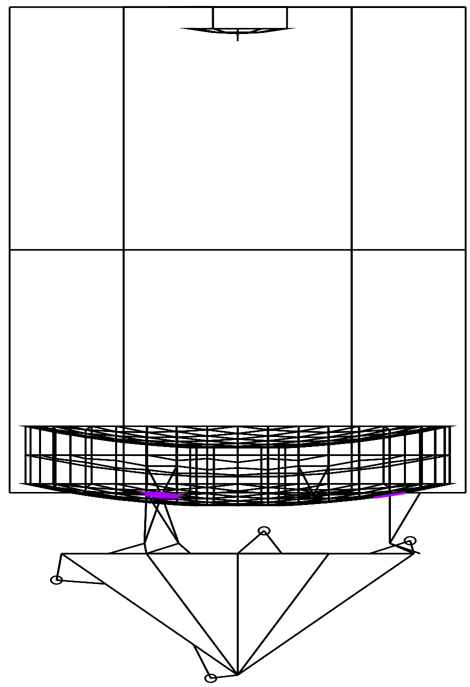

Figure 2: Side View Showing PM and Aft Metering Structure

1. PM = Primary Mirror (28” OD light-weight)
2. SM = Secondary Mirror (6.5” OD solid)
3. FM1 = Fold Mirror #1 (solid)
4. TM = Tertiary Mirror (solid)
5. FM2 = Fold Mirror #2 (solid)
6. FP = Focal Plane

The PM is modeled as a 3D shell structure with front plate, back plate, and internal core structure. The mount pads, adhesive and bipod flexures are included in the model. The SM is modeled as a 2D shell with edge flexures. The other optics are represented as lumped masses supported on an aft metering structure.

THERMAL MODEL AND ANALYSIS

The thermal model and orbit used for the analysis are shown in Figure 3. A thermal enclosure has been added around the metering structure and solar arrays have located on the exterior. The solar arrays are driven by articulators that automatically track the sun during the orbit. Temperatures presented here are for the illustrated point in the orbit (just before the subsolar point). This orientation produces uneven heating on the telescope body and drives gradients in the mirrors.

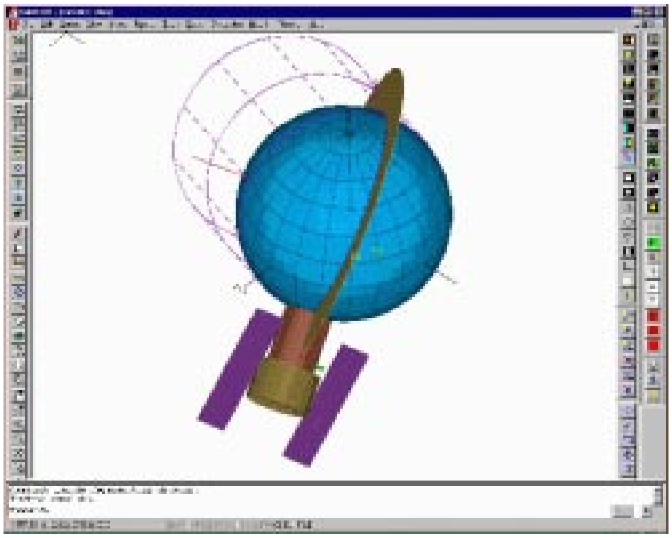

Figure 3: Thermal model and orbit used for optical telescope demonstration model

Radiation exchange factors, orbital heating rates, and the conduction and capacitance matrix were computed using Thermal Desktop/RadCAD. The radiative analysis was carried out using a full Monte Carlo raytracing process including the use of specular surface properties. Nearly all of the thermal model was generated automatically, even so, in a few places it was desired to create arbitrary nodes and conductors, for example to provide a simple model of the heat loss through wire bundles to the solar array drives. All modeling methods are supported simultaneously in Thermal Desktop: arbitrary network connections, finite difference geometry, and finite element geometry.

Temperatures were solved using SINDA/FLUINT, and results mapped onto the NASTRAN structural model. Thermal Desktop's Case Set feature [5] was used to automatically launch radiation calculations, conduction and capacitance generation, SINDA/FLUINT calculations, and post processing from within Thermal Desktop. The full up thermal model consisted of 746 thermal nodes.

Thermal Desktop communicates with both CAD and FEM systems. In this demonstration case, thermal and structural models were generated directly by the analysts, although CAD drawings could have been used as the basis for interactive model creation. The thermal model was created by first importing the NASTRAN (FEMAP and I-DEAS also supported) structural model into Thermal Desktop and then making changes appropriate for computational efficiency and thermal accuracy requirements. Extensive use of SINDA/FLUINT submodels were employed to facilitate the organization of the thermal model.

It was felt that the number of elements used to model the tubular body of the telescope was excessive for thermal purposes. Rather than analyze the tube as consisting of a collection of many flat elements, they were replaced by a single Thermal Desktop cylinder with a coarser nodalization. Using the interactive "snap" method of Thermal Desktop, a few mouse clicks is all that is required to generate the cylinder. In a similar fashion, rings used for the metering support structure and for the ends of the bus section were modeled using disk surfaces, again with a nodalization appropriate for thermal accuracy requirements. Simple finite difference rectangles were sufficient for accurately modeling the effect of the solar arrays.

A significant difference between the thermal and structural models exist for the spider and primary mirror metering structure. In the structural model, beam elements and mass nodes are all that are necessary to simulate the desired mechanical behavior for stress and dynamics calculations. This structural representation, however, is missing necessary information to carry out the thermal analysis. For the thermal model, 2D planar elements were used so that radiation exchange could be properly modeled and so that gradients could be calculated to map onto the beam elements. Like the structural model, the thermal representation also contains simplifications of the real part that make it efficient for thermal analysis.

This portion of the spacecraft illustrates the need for each discipline to be free to generate computer models independent of one another, so that only the salient details are captured in each representation. Not only does this maximize the efficiency of the model for each discipline, but also the data that is generated matches more closely with the goal of the analysis. Even if we had infinite computer resources such that a micro-detailed model could be generated that simultaneously satisfied all engineering disciplines, simplifications would still be desired in order to reduce the burden of extracting useful information from the enormous amount of generated data. Simplifications are made not only for tractability, but also to most clearly represent the physics of the problem at hand.

The thermal model of the primary mirror is shown in Figure 4. The top figure shows the mirror mounted on the metering structure, and the bottom figure shows the detail used for the mirror core. Unlike the spacecraft body and metering structure, no geometric simplifications were appropriate for the thermal model of the primary mirror. Both the structural and thermal model use a detailed finite element mesh. In analyzing optical performance, accuracy of the gradients present in the mirrors are paramount. Influences of the core structure and the mounting points simply cannot be accurately predicted by replacing this mirror with simple TRASYS or TSS surfaces. Supporting detailed thermal/structural/optical analysis was the primary reason for adding direct support of FEM to Thermal Desktop.

The thermal model illustrates three important modeling aspects:

1. Complexity was reduced without affecting desired accuracy by using thermally efficient, mathematically precise curved surfaces for the spacecraft body.

2. Independent thermal and structural abstractions were

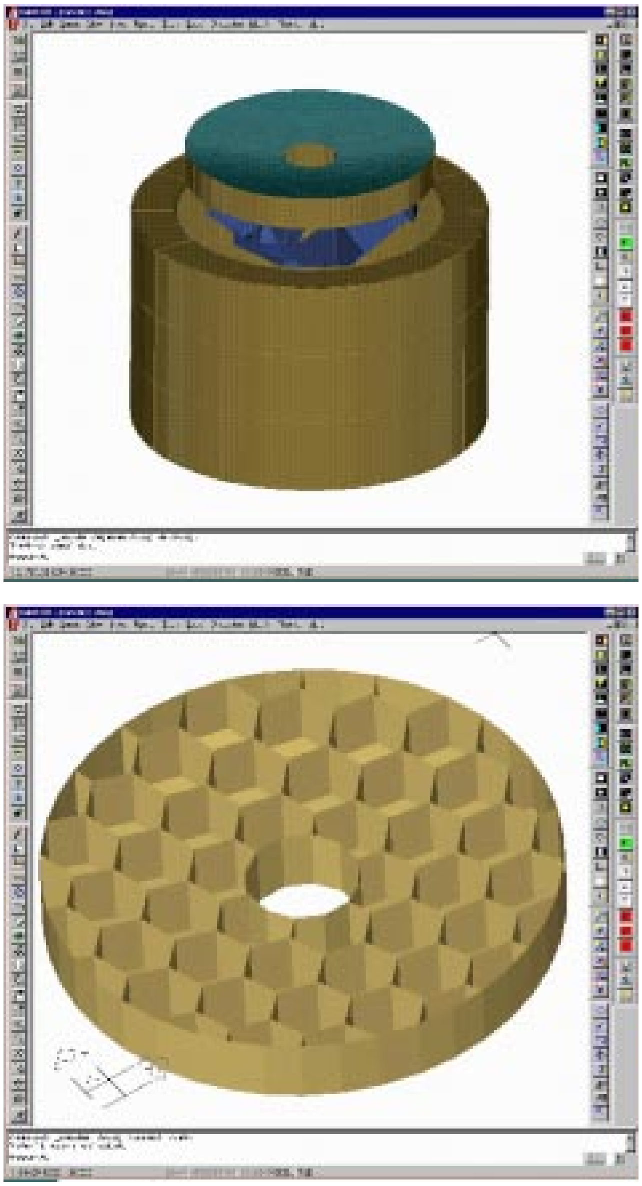

Figure 4: Thermal representation of primary mirror and metering structure

used for the mirror metering structures.

3. Detailed finite element thermal models were used where accuracy would have been unacceptable with further simplification.

The effect of the solar loading in producing gradients in the spacecraft body is shown in Figure 5. Local warming of the spacecraft is also present in the regions close to the solar arrays. Gradients can be seen in the spider locating the secondary mirror due to conductive contact with the space-craft shell. Temperature distributions in the face and body of the primary mirror are shown in Figure 6. The effect of the mounting points can be seen on the back face of the mirror, most notably the cold spot near the lower left edge. A slight increase in temperature can be seen due to the other two mounting locations.

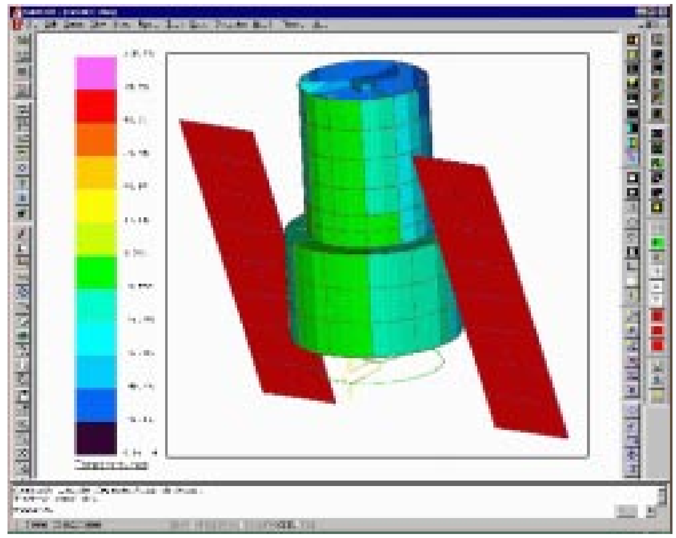

Figure 5: Temperatures displayed on thermal model of demonstration telescope

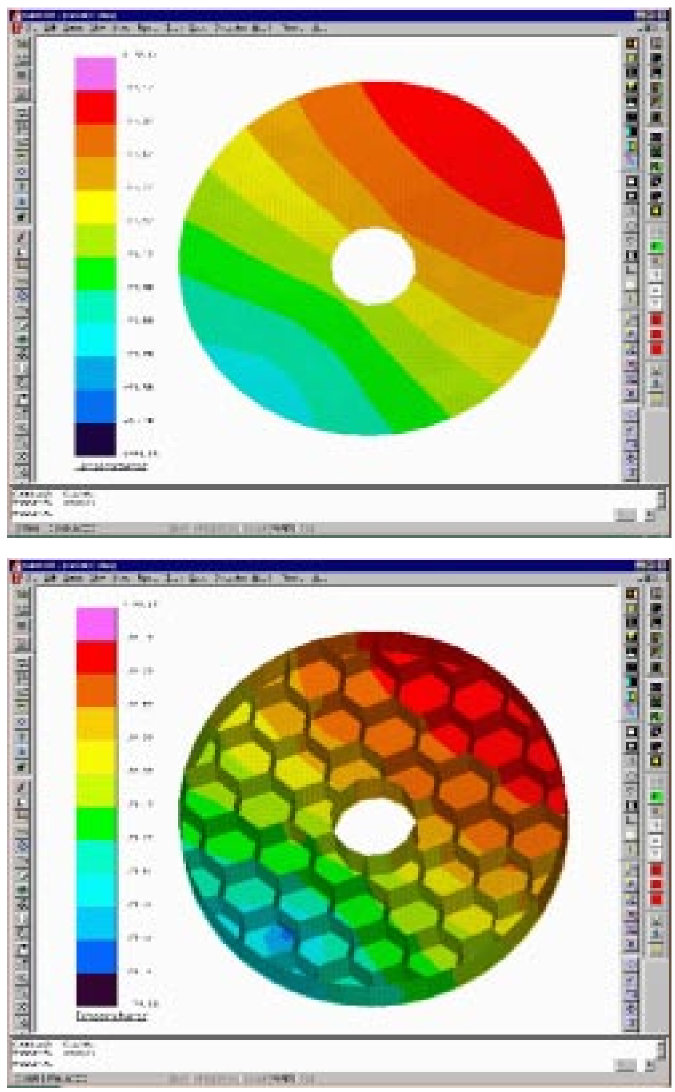

Figure 6: Temperatures for primary mirror

DATA MAPPING

In an integrated engineering environment required to design complex thermal/structural systems, improvements to thermal tools have little consequence if the results cannot be accurately transmitted to the structural engineers. Previous approaches to automating the temperature mapping to structural models have been ineffective, most based on taking a collection of thermal points with associated data and attempting to map this to a new set of structural points.

Temperature mapping has suffered for two reasons:

1. The thermal model is not built with modeling primitives conducive to interpolating results everywhere in the domain of the model.

Using TRASYS/TSS modeling primitives, arbitrary, non-conic shapes must be modeled using one-node polygons, which cannot be interpolated. Low nodal density surfaces suffer from inaccuracy due to extrapolation to the edges. Indeed, had the core of the mirror been constructed with typical one-node polygons for the thermal model instead of quad finite elements, no information of how the temperature varies in individual core segments would be present in the model, only the bulk temperature of the webs.

2. Algorithms for mapping temperatures have been too simplistic and introduce additional error.

A common approach is to map a handful of temperatures by hand and then perform a steady state solution using the structural mesh. This often leads to strange temperature distributions consisting of local hot spots at the temperature defined locations. Another simple approach is given an x,y,z location, find the closest thermal node and use that as the temperature of the structural node. An attempt to improve this scheme is to use some sort of inverse distance weighting to average the results of a collection of thermal nodes near the given point. This approach can produce incorrect results when the thermal model consists of closely spaced surfaces (like a honeycomb panel or mirror core). A structural point may lie exactly on a thermal surface which should be used to compute the temperature, however, the closest thermal node may not lie on this surface containing the point, but actually be on a different surface located near the point.

The correct approach is to take the collection of x,y,z locations for each structural node and interpolate using the geometric information contained in the thermal model. This becomes more difficult than dealing with a collection of thermal points, since proximity tests must be developed for each type of thermal modeling primitive. The algorithms are very similar to those used by RadCAD for ray/surface intersection when calculating radiative quantities.

The first step is to find which thermal object (arbitrary node, finite difference surface, 2D finite element, or 3D finite element) the structural point lies on, near, or in. If the point is not contained by a thermal object, the closest object must be found. This test is specific to each type of thermal object (cone, paraboloid, quad, brick, etc...). If the point is not directly contained by an object, all objects must be tested to determine the closest.

The effort in correctly developing the algorithms to test for proximity for the variety of thermal modeling primitives is the main reason simpler approaches have been taken. However, previous work performed in the development of RadCAD was utilized for the data mapping algorithm. In addition, the speed of the model mapping is increased by orders of magnitude due to the unique incorporation of an oct-cell partitioning algorithm to weed out surfaces that are distant from the structural point to be mapped. The time required to compute temperature data for 980 NASTRAN grid points was approximately 30 seconds on a 200 Mhz Pentium Pro processor for this demonstration model.

Another significant improvement has been made to the data mapping algorithms. All thermal objects use the maximum amount of information to determine the temperature at a given point. Bilinear interpolation is used for finite difference surfaces and all planar finite elements. Trilinear interpolation is used for all solid finite elements.

Only the orthogonally gridded finite difference surfaces, the triangle and the tetrahedral solid, admit a direct solution to mapping a given x,y,z point into local parametric coordinates that can be used with the object’s shape functions to interpolate temperature. Iterative algorithms were developed to map an x,y,z point into parametric u,v space for quadrilateral elements and into parametric u,v,w space for solid wedges and bricks. The alternative approach is to decompose quadrilaterals into triangles, and solids into tetrahedrals. Although much better than a closest node approach, the original isoparametric contours are not preserved and artificial discontinuities can be introduced. The algorithms used by Thermal Desktop to map temperatures to structural points use the same shape functions used to compute the temperatures, resulting in the maximum fidelity in mapping data onto the structural model.

The data mapping command may be invoked by selecting a toolbar icon or selecting from a pull down menu. The FEM input file is specified as well as a file that will be generated with temperatures in the FEM code’s format. An optional tolerance may be specified if the structural points do not exactly lie in or on thermal modeling primitives. The Thermal Desktop model mapping input form and an example of temperatures mapped to the NASTRAN model of the telescope are shown in Figure 7. The effect of the stiffening rings near the base of the telescope in equalizing the temperatures by conduction is apparent as is the influence of the warm solar arrays.

CONCLUSION

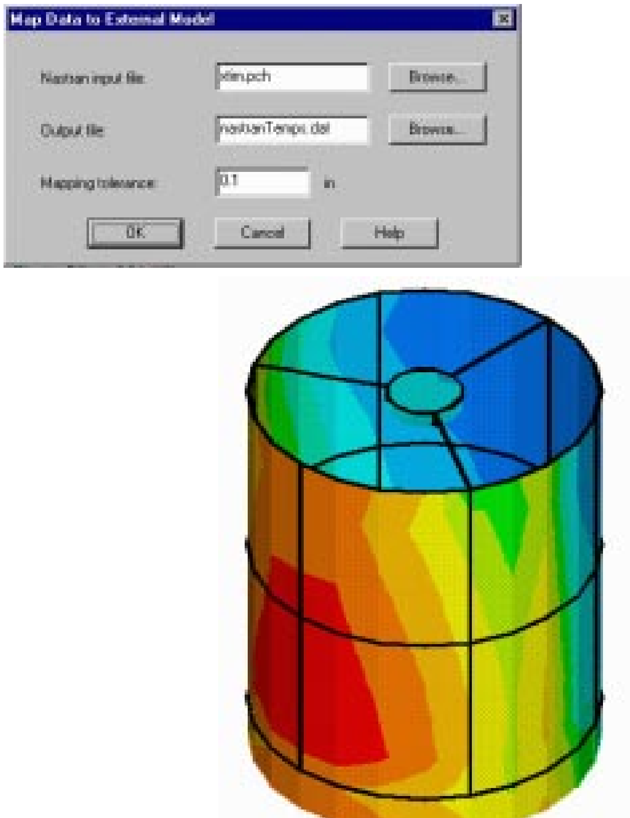

Figure 7: Temperatures mapped to NASTRAN structural model

Many problems were identified and solved to improve integrated thermal/structural analysis. Thermal Desktop is the first system to efficiently combine CAD, FE, FD, and arbitrary thermal network methods to allow the engineer to build both efficient and accurate thermal models. All types of modeling methods may be used simultaneously so that appropriate choices may be made regarding accuracy, model mapping needs, and efficiency.

By integrating FE methods into the traditional FD/network environment, new capabilities are provided without sacrificing present modeling approaches. A consistent control volume view of FE coupled with nodal based radiation and orbital heating rates allows FE and FD methods to coexist in the same model and be used with familiar solvers such as SINDA/FLUINT. These improvements combined with new algorithms employed in the data mapping process, greatly improves the integrated thermal/structural analysis process for complex systems.

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