

Integrated Analysis of Thermal/Structural/Optical Systems

B. Cullimore, T. Panczak, J. Baumann

C&R Technologies, Inc. (www.crtech.com)

Dr. Victor Genberg

Sigmadyne, Inc. (www.sigmadyne.com)

Mark Kahan

Optical Research Associates, Inc. (www.opticalres.com)

Copyright © 2002 Society of Automotive Engineers, Inc.

ABSTRACT

Productivity bottlenecks for integrated thermal, structural, and optical design activities were identified and systematically eliminated, making possible automated exchange of design information between different engineering specialties.

The problems with prior approaches are summarized, then the implementation of the corresponding solutions is documented. Although the goal of this project was the automated evaluation of coupled thermal/optical/structural designs, significant process improvements were achieved for subset activities such as stand-alone thermal, thermal/structural, and structural/optical design analysis.

INTRODUCTION: PROBLEM STATEMENT

Structural, thermal, and optical engineers typically work independently of each other using unrelated tools, models, and methods. Without the ability to rapidly exchange design data and predicted performance, and therefore to influence each other's efforts, the prior state-of-the-art for the design of advanced optical systems was inadequate: it has henceforth resisted attempts to achieve the ideals of concurrent engineering. Limited success has been achieved at a very top-level (suitable for conceptual design studies), but only by approximating or neglecting the detailed design tasks that the engineering specialist must perform in later mission phases.

Without the ability to work concurrently, the disciplines of thermal control, structures, and optics levy worst-case performance requirements on each other such that each specialty can contribute to a design independently. The optical engineers dictate distortion limits to the structural engineer, who then dictates limits on temperatures and gradients to the thermal engineer. Requirements are derived, then flowed down. The thermal and structural engineers blindly obey these limits under all operational conditions, thereby satisfying the optical performance requirements.

That approach results in a stack-up of margins and inevitably to over-design, to the point of rendering advanced mis-

sions such as NASA's Next Generation Space Telescope (NGST), with its cryogenic large aperture optics, difficult to achieve without an integrated design approach. For example, temperature gradients in a mirror support structure are inconsequential as long as the required optical performance is achieved, yet *derived* limits on such gradients often become a design driver for thermal control specialists.

DESIGN PROCESS INTEGRATION

This paper describes the first step, which was to achieve tighter and smarter communication pathways between existing tools such as ORA's CODE V® optical analyzer, the MSC/NASTRAN® structural analyzer, and C&R's SINDA/FLUINT and Thermal Desktop®. Once this was achieved, the ability to externally drive the design towards an optimum was implemented and tested, as described in Reference 1.

Previous innovations by the development team had eliminated many of the stumbling blocks that had stymied earlier attempts to achieve a tight integration between thermal control, structures, and optics. These prior advances include a finite element-compatible and CAD compatible thermal radiation analyzer (Ref 2), thermal tools compatible with structural programs (Ref 3), optimizing thermal/fluid solvers (Ref 4), and integrated structures/optics design.

The theme of "intelligent integration without sacrificing the tools or methods of each specialty" was carried forward into the idea of providing system-level design optimization tools. In other words, the goal of this development was not merely an integrated tool suite, but also one that can automatically explore the design space to find an optimal design that meets required optical performance under all structural load cases and thermal environments.

As will be seen, however, the end product (OptiOpt™, for "optimized opto-mechanical design") does not have to be applied in its entirety in order to achieve significant improvements over prior design practices. Rather, improvements to the underlying thermal and optical codes and the generation of general purpose model conversion and mapping schemes are useful in and of themselves. In

fact, the development of those underlying pieces occupied most of the three year development, leaving the demonstration of the final integrated system (Ref 1) exciting, but somewhat anticlimactic.

PRIOR STATE-OF-THE-ART

To appreciate the advances that have been made, a reminder of the prior state-of-the-art is necessary.

PRIOR PROBLEMS WITH THERMAL/STRUCTURAL INTEGRATION

Integration of thermal and structural analysis codes has long been sought, but had been prevented by incompatibilities in previous tools. Separate analysis models are often built for each discipline. For example, a TRASYS or TSS model might be built “from scratch” for the thermal representation, and a NASTRAN model might be built for the structural representation. Temperature data from the thermal model is then often mapped to the structural model by hand, or by generating a custom program to map thermal node temperatures onto structural FEM nodes. This process is shown in Figure 1. (This is to be compared with Figure 2, which represents the culmination of the integration development effort. The remaining weak links in Figure 1 have been subsequently eliminated, as is discussed in Reference 1.) Figure 1 is somewhat simplified as there are other interfaces required for refractive systems (e.g., thermal to optics, stresses to optics, etc.).

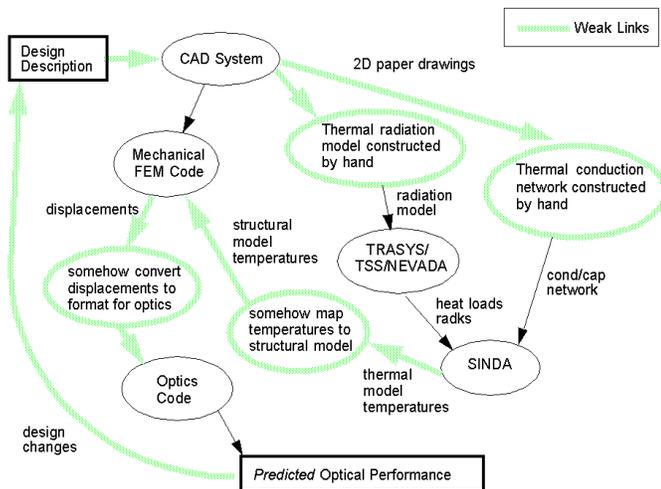


Figure 1: Prior Process: Weak Integration

Changes in the design or in any of the analysis models usually renders the custom conversion program invalid. Often one of the analysis models will be changed without the other engineers’ knowledge. Shortcuts are usually 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 highly prone to error. Intrinsic inaccuracies in this mapping procedure lead to artificial deflections and therefore erroneous predictions of optical performance.

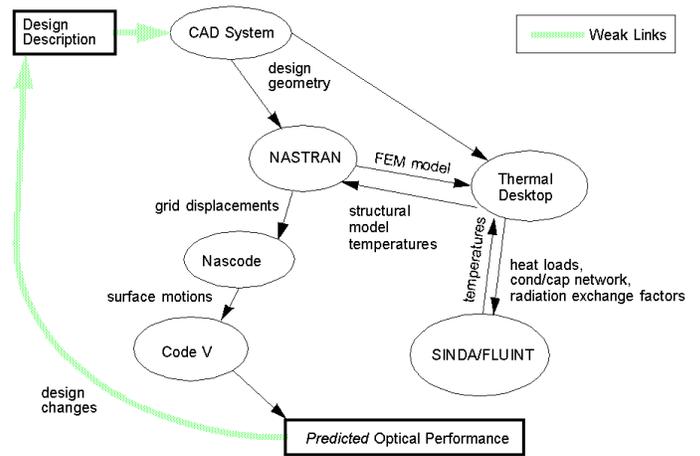


Figure 2: First Step: Streamlined Process

A common but fundamentally flawed approach was to use structural FEM models *directly* as thermal models (examples abound: TCON/FEMAP, PATSIN, FEM/SINDA, TAS/FEMAP, new versions of TSS/CONCAP, etc.). 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. Otherwise finite difference centroid methods introduce additional errors when returning temperatures to the structural program. Yet even when centroid conversions 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 that are presented next.

THE MODEL MAPPING/SIMPLIFICATION PROBLEM

One reason for the failure of the above FEM-translation approach is that the structural FEM models must either be used directly, or must be simplified. If they are used directly they usually result in intractable thermal models at the system level due to excessive run times or other size limits. If they are simplified then the user loses the ability to map directly (or at least intelligently) back to the original FEM mesh, which is a key requirement for predicting temperature-induced deflections. Brute-force mappings such as “nearest node” are often used, which produce artificial distortions.

C&R’s Thermal Desktop®, a CAD-based and FEM-compatible tool specifically developed to solve problems associated with concurrent thermal engineering, played a key role in the development of OptiOpt. Unique model mapping methods were developed for Thermal Desktop that solved many of the problems noted above. These methods are generalized enough that the thermal and structural models need not have the same heritage: they can be developed independently (albeit perhaps from the same CAD-based design geometry) and yet automatically corresponded to

each other intelligently and with a minimum of artificial distortions. Previously, Thermal Desktop had been expanded to include *suppressed nodes*, by which imported structural FEM meshes are intelligently simplified, while preserving a perfect mapping (at least in steady state solutions) back to the underlying structural model.

THE RADIATION PROBLEM

Another related reason for the failure of the “direct-from-structural-FEM” approach is in interfacing the FEM model with the thermal radiation analysis tool.

One approach is to compute thermal radiation effects using isothermal element surfaces. This requires a conversion of the energy exchanged by radiation based on the elemental areas to nodal quantities. Energy radiating from a node is taken as the average over the elements to which it is connected. This is a numerical relaxation step which smooths the radiation loads on the model, and therefore underpredicts thermal gradients and therefore thermal-induced distortions. Furthermore, prior radiation tools such as TRASYS, NEVADA, etc. are usually overwhelmed by the number of radiation surfaces present in a typical FEM model and analysis becomes intractable for even the simplest representations due to excessive run times or other software or machine limits.

The biggest obstacle for the tight integration of thermal and structural models has been the thermal radiation analyzer. Fortunately, C&R’s RadCAD® (a module of Thermal Desktop) was designed from the ground up to satisfy the need for compatibility with finite element models. RadCAD supports finite element meshes directly, computing node-to-node radiation exchange factors and nodal orbital heating rates using a non-isothermal formulation. Accuracy is improved two-fold over current approaches, first by removing the isothermal restriction, and second by eliminating the aforementioned relaxation of loads caused by element centroid to nodal point conversion.

PRIOR PROBLEMS WITH STRUCTURAL/OPTICAL INTEGRATION

The integration of structural and optical codes suffered from incompatibilities similar to those of thermal/structural integration. Displacement data from a structural analysis program like NASTRAN had to be converted into a representation suitable for optical analysis in a program such as CODE V®. This often involved significant data manipulation to convert coordinate systems, units, numbering schemes, and formats. The data manipulation was performed by special purpose codes or, as is still often the case, by hand.

Prior approaches to telescope design rarely combined enough optical analysis with mechanical analysis to allow quick design evaluation. Error budgets often lack sufficient analytic foundation due to a lack of combined optomechanical software. Tracing the source of unwanted image motion requires a time consuming sequence of several

analyses involving transfer of data between structural and optical codes.

The average motion of each optical surface affects the pointing alignment, focal shift, and wavefront error. In addition, the distortion of each optical surface in the form of curvature change and higher order aberrations has additional effects on the wavefront error and focal shift. To accurately predict the optical performance, each of the quantities must be passed to the optical analysis code. In CODE V, surface distortion may be represented as a regular array of surface displacements or as best-fit set of Zernike polynomial coefficients. Neither representation is easily obtained directly from a finite element program, and thus special interpolation or surface fitting is required. Even the use of these special codes required significant additional data manipulation to conduct a subsequent optical analysis. Furthermore, it is often necessary to separate rigid body motions from higher order changes to allow for simulation of active alignment, cryo-alignment, and/or cryo-nulling, and this adds to the complexity of curve fitting and the bookkeeping rigor needed to avoid double billing of errors.

The above discussion applies to the analysis flow. As for the design process, the prior approach was to totally design (and optimize) the optical system independent of any structural behavior. The optical support and metering structure was then designed (and optimized) with all optical parameters as prescribed quantities. There was little if any chance for the structural behavior to affect the optical design. This approach often prevents any design modification of an optical parameter to desensitize the system to structural response, resulting in degraded performance.

The integration of structural and optical analysis requires a code which evaluates, modifies, and passes the structural response to the optical code. The response must include average surface motion, curvature change, higher order surface distortions, and actuator influence functions. The input and output formats must be consistent with the analysis codes, i.e. NASTRAN and CODE V. A code (working name “NASCODE”) was developed by Sigmadyne that performed these functions. NASCODE functionality was later incorporated into a commercially available product, Sig-Fit™.

THERMAL SOFTWARE ENHANCEMENTS

This section summarizes the improvements made to Thermal Desktop, RadCAD, and SINDA/FLUINT to support the development of OptiOpt. These improvements represent a very significant expansion of functionality for most thermal design and analysis tasks, not just thermo-opto-mechanical ones.

PARAMETRIC THERMAL DESKTOP

One of the most thorough revisions undertaken was the parameterization of Thermal Desktop: the ability to define inputs via algebraic expressions and/or on the basis of user-defined variables (*symbols*, analogous to SINDA/FLU-

INT registers). Almost all data fields (dimensions, translations/rotations of articulators, material and optical properties, orbits and other boundary conditions, etc.) can now be specified using this spreadsheet-like capability.

Figure 3 depicts the Symbol Manager form in Thermal Desktop, containing a partial set of the symbols used to define the demonstration model (described later). Figure 4 shows how the thickness of the telescope cylindrical shell of that model was defined indirectly as "ShellThk" (current value of 0.02) such that this thickness can be varied automatically.

This example illustrates the importance of fully parameterizing Thermal Desktop. Now, not only can the user simply update a few values and have the changes propagate through their model, but such changes can also (with the improvements that are described later) be commanded externally as part of an automated top-level design optimization process.

Symbols values can be temporarily overridden within an analysis task using the Thermal Desktop Case Set Manager. Figure 5 shows how Thermal Desktop symbols can also be passed to SINDA/FLUINT as registers within the Case Set Manager. (Normally, only a subset of Thermal Desktop symbols become SINDA/FLUINT registers.) These registers/symbol values can then be manipulated

within SINDA/FLUINT, including being updated and then sent back to Thermal Desktop for new calculations.

SPEED IMPROVEMENTS

Thermal Desktop and RadCAD were already very fast to execute. However, automated optimization, which was the ultimate goal of this concurrent engineering project, requires tens and perhaps hundreds of repeated design reevaluation. Therefore, an even greater premium is placed on fast run times and reasonable models. (This fact also underscores the importance of the dissimilar model mapping methods, which allowed the thermal model execution to be honed for its tasks without using a structural model directly and often inappropriately as a thermal model.)

Recalculation Avoidance--Execution from within an optimization environment often differs from calculations performed "manually" because repetitive calculations are requested; the external optimization driver has no knowledge of what minimum amount of recalculation is required given a change in any one design variable. An extensive internal utility was added to Thermal Desktop and RadCAD to make sure that any previously available recalculations are used, intelligently avoiding unnecessary recalculations.

For example, if no external dimensions, orbits, optical properties, etc. have changed from the last run, then orbital

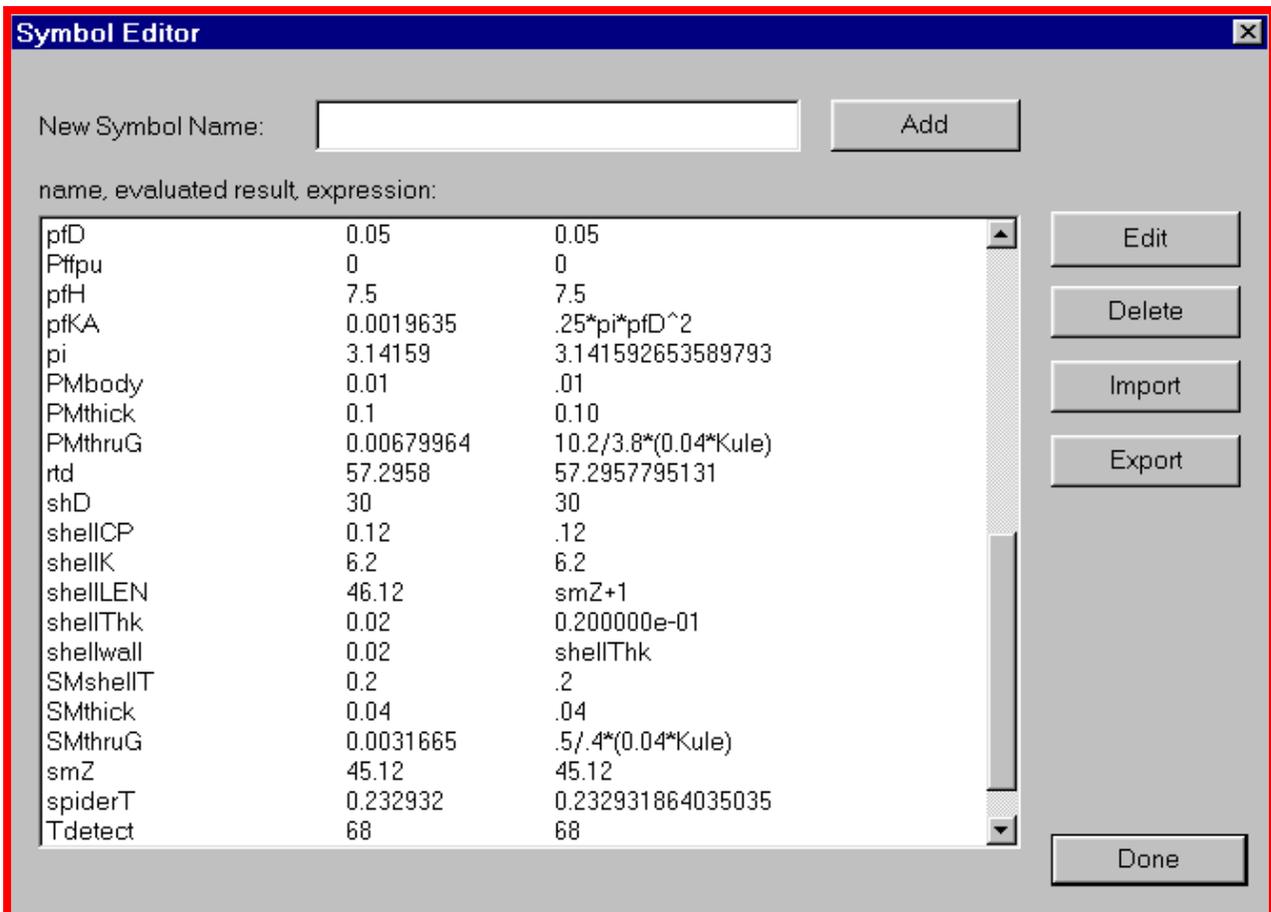


Figure 3: Thermal Desktop Parametric Inputs via Spreadsheet-like Symbols and Expressions

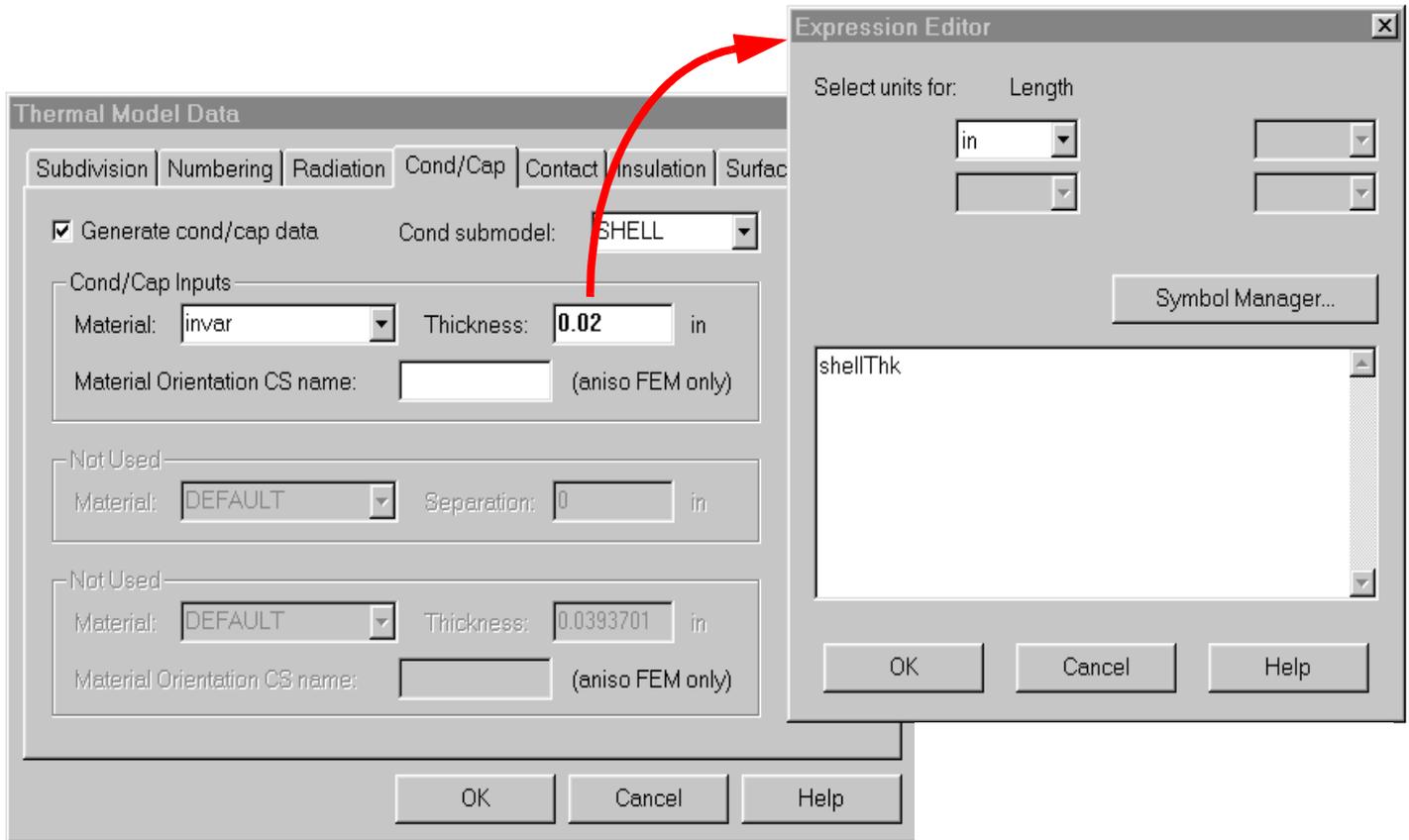


Figure 4: Example use of Symbols to Indirectly Define the Shell Thickness of a Cylinder Representing a Telescope Structure

fluxes need not be updated. If only thicknesses of surfaces have changed, radiation exchange factors (RADKs) need not be recalculated. In the demonstration problem described later, these checks reduced thermal run times by about a factor of about 5 to 10.

As with other improvements listed in this section, this improvement will be welcomed by any analyst, even those performing “manual” updates of a design analysis, including simple parametric analyses.

Contact Conductance Improvements--As a result of excessive run times during repeated recalculations, revisions were made in the algorithms used to search for contact conductances and estimate areal intersections. The results represented an approximate tenfold increase in speed.

FULL ACCESS TO SINDA/FLUINT

SINDA/FLUINT features its own Advanced Design modules for optimization, correlation/calibration, and reliability engineering (Ref 4, 5, 6, 7). These can now be fully accessed and utilized from within Thermal Desktop, allowing its symbols to become design variables for optimization, uncertain parameters for calibration to test, or random variables for statistical design. Also, all SINDA/FLUINT logic blocks can now be accessed from within Thermal Desktop using a new color-coded text editor. The top part

of Figure 6 illustrates the main control panel for accessing this logic, while the bottom part of that figure shows the access to the Advanced Design modules.

Together with the dynamic run option explained in the next subsection, Thermal Desktop and SINDA/FLUINT can now be very tightly linked. Again, this represents a very powerful feature even for stand-alone thermal analysis. However, it also represents a prerequisite step towards OptiOpt, since the advanced design modules in SINDA/FLUINT became the access port for external connections.

DYNAMIC THERMAL DESKTOP

Thermal Desktop is an interactive program. Unlike SINDA/FLUINT, it has neither a batch mode nor a text input file nor neutral file format. Traditionally, Thermal Desktop was run once, creating SINDA/FLUINT inputs, and then SINDA/FLUINT was run many times provided that no relevant dimensions, properties, orbits, etc. have changed. More commonly, SINDA/FLUINT may also be run in a “one button” mode from Thermal Desktop using its Case Set Manager to generate and execute a custom SINDA/FLUINT run that is somewhat hidden from the end user.

However, during the course of OptiOpt iterations Thermal Desktop calculations must be updated in response to external commands to reset data and regenerate new results.

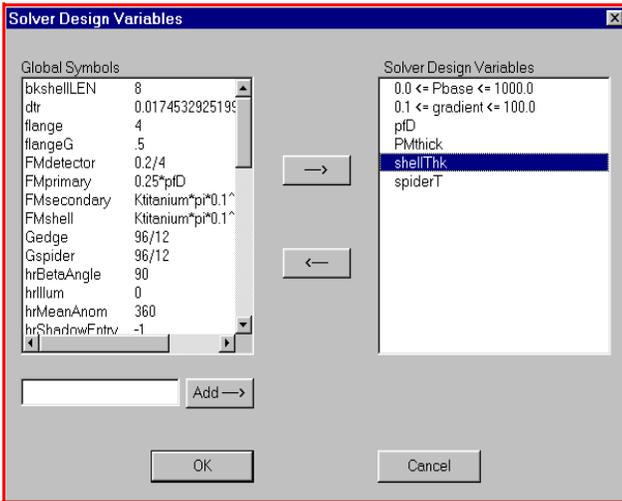
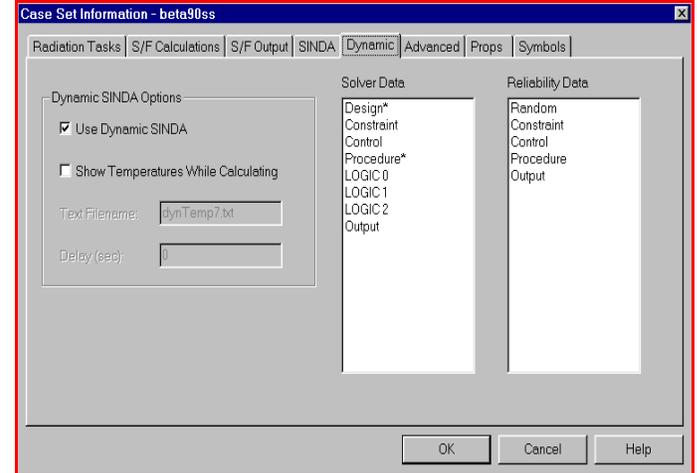
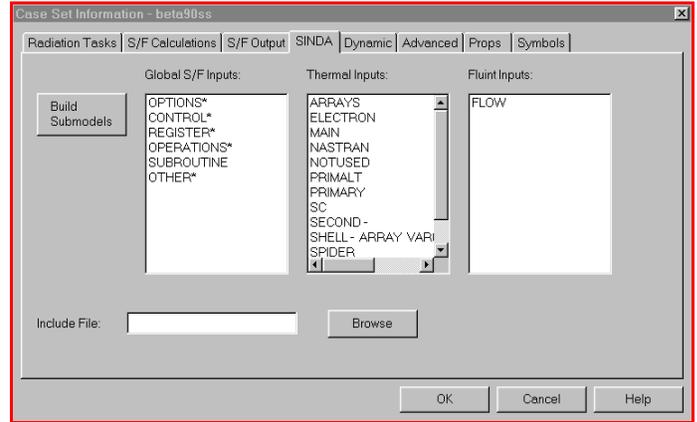
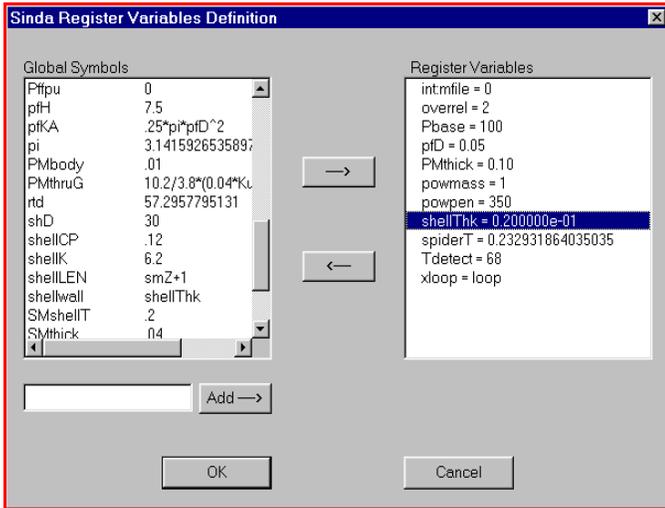


Figure 6: Full Thermal Desktop Access to SINDA/FLUINT

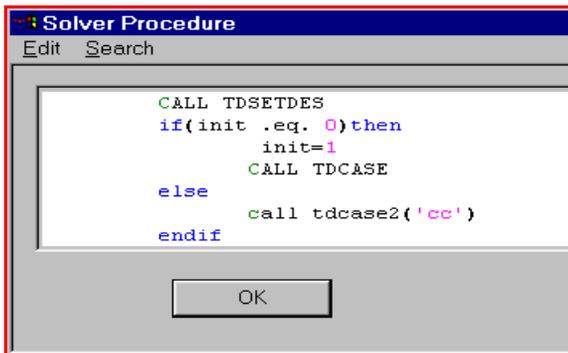


Figure 5: Thermal Desktop Symbols can be exported as SINDA/FLUINT Registers (top), Assigned as SINDA/FLUINT Design Variables (middle), and Updated from within SINDA/FLUINT (bottom) or other programs

lations, to display user-defined messages in a scrolling text window, to reread NASTRAN files and remap the current solution to NASTRAN format, to update its postprocess display, etc. Such commands can be embedded in the SINDA/FLUINT logic blocks as Fortran subroutine calls (such as those that can be seen in the bottom part of Figure 5):

- CALL TDSETDES: send current design variable values to Thermal Desktop
- CALL TDCASE: redo current Thermal Desktop conduction, capacitance, radiation calculations
- CALL TDCASE2('cc'): redo only the conduction/capacitance calculations.

Significance of this By-product--The ability to update Thermal Desktop calculations dynamically from within SINDA/FLUINT is revolutionary for thermal engineers, and is therefore a major by-product of the OptiOpt development. Thermal Desktop is classified as a GMM: Geometric Math Modeler. Others of that type of software include TRASY, TSS, ESARAD, Thermica, and NEVADA. SINDA/FLUINT is a TMM: Thermal Math Modeler, others of which include SINDA/G and ESATAN. In the forty year history of such codes, GMM codes and TMM codes have been run sequentially and separately with little if any interconnection.

COM Interface--To accomplish this external command capability, a COM-based API was added, and a command structure and syntax was created such that Thermal Desktop would accept and respond to COM commands, allowing an external program to drive it.

Thermal Desktop can now be externally commanded to accept new symbol values, to update all or part of its calcu-

The assumptions underlying this separation of codes include (1) radiation is assumed grey within its wavelength band (solar or infrared), (2) optical properties are assumed constant, and (3) geometry, if variable, was a function of time only and not of temperature or some other variable that could not be known a priori. These assumptions have been adequate for many spacecraft analyses, provided that certain components such as thermal louvers could be modeled abstractly rather than directly.

A dynamic interface between Thermal Desktop, especially combined with the SINDA/FLUINT advanced design modules, *enables for the first time* the following important classes of analysis:

- automatic calibration of models to test data including uncertainties in illumination and in optical properties (absorptivity, emissivity, specularity, transmissivity)
- automatic search for worst-case design cases including variations or uncertainties in environments (including orbit), vehicle orientations, solar panel locations, etc.
- automatic sizing of radiators, selection of optical properties, location of components
- automation of parametric sweeps, sensitivity studies, and reliability estimations (probabilistic evaluations) involving optical properties, positioning/orientation, orbital specifications, etc.

NASCODE: NASTRAN TO CODE V CONVERSION

NASCODE is Sigmadyne's conversion utility that reads both the NASTRAN and CODE V models and then creates semi-custom data conversions. These conversions enable CODE V to assess the optical degradations that result from NASTRAN-predicted displacements of optical components and surfaces, including thermoelastic deflections.

NASCODE makes the following assumptions:

1. Linear small displacement theory applies so linear superposition and scaling can be used.
2. All displacements are measured from the original surface.
3. Small angle approximations apply.

For common optical systems these assumptions are not restrictive.

In NASCODE, the user specifies which Zernike terms to fit, and has the following options:

- Standard Zernike terms (up to $n=8$, $m=6$)
- Best fit plane only (BFP)
- BFP and power
- Standard Zernike + extra spherical terms ($n=12$)
- Standard Zernike user-specified terms
- Fringe Zernike (Wyko & Zygo order)
- Aspheric polynomials (even only)

- Aspheric polynomials (even and odd)
- XY polynomials

The program allows for a centrally located aperture and obstruction of rectangular or elliptic (including circular) shape on any optical surface. Any nodes outside of the aperture or inside of an obstruction are automatically eliminated from the surface fit operation. Any arbitrarily shaped or located aperture and obstruction are easily incorporated into the finite element model through the use of surface elements, though special treatment of Zernike polynomials may well be required in such cases. Off-axis optics can be analyzed using these features.

NASCODE execution is divided into two phases to minimize the cost of repetitive computations. Nascod1 is run once per problem set-up. It reads the NASTRAN node data, writes a file for NASTRAN that includes the Zernike equations per the input options, then writes a short-cut file for NASTRAN and Nascod2 (the second pass) containing units and other application-specific data.

During iterative execution, only Nascod2 is called. Nascod2 reads not only the input file left for it by Nascod1 but also the NASTRAN "punch" and output files. It then writes a concise parameter file for reporting NASTRAN outputs (e.g., mass, frequencies, stresses) as well as CODE V inputs such as decenters and Zernike coefficients for each optical component.

NASCODE functionality has been incorporated by Sigmadyne into a commercially available product, SigFit™.

CODE V ENHANCEMENTS

An API to CODE V® was created by ORA in support of the OptiOpt development. It consists of a simple but powerful set of method calls. These calls allow external programs to start and stop CODE V, as well as issuing CODE V commands in the same manner as a user typing at a standard CODE V command prompt. All CODE V output can also be directed to a text file if desired. Also, CODE V graphics can be saved to files in Postscript or Encapsulated Postscript (EPS) formats.

The interface can also be streamlined by the use of CODE V's internal macro language. For example, a macro could be written to apply a complex set of thermal and structural perturbations to an optical system, and to return only the RMS wavefront error in the return output string. This reduces the need for text parsing by an external program (e.g., multidisciplinary optimization software).

This API was not actually used in the demonstration problem (Ref 1) in part because of the difficulties encountered with third party software, and in part because CODE V can easily be run in a batch mode invoking predetermined macros with little overhead cost. However, the API represents an investment in a more complete infrastructure for future end users and other customized design environments.

CONCLUSIONS

Automated and accurate exchange of data is now possible between divergent thermal, structural, and optical models that have been built independently by teams of specialists using industry-standard software.

C&R's Thermal Desktop, designed from the start to eliminate critical problems in concurrent engineering, was significantly expanded to include parametric modeling, to accelerate recalculations, to accept external commands from SINDA/FLUINT and other COM-based codes, and to export updated calculations on demand. For example, the above features can be used to dynamically command Thermal Desktop in a script-like fashion to:

1. adjust one or more dimensions and properties parametrically
2. recalculate radiation and conductance/capacitance factors and export them to an awaiting SINDA process
3. reimport SINDA results
4. reimport a disparate but related NASTRAN model (that might itself have changed from the last iteration)
5. map the SINDA results to the NASTRAN data points, then export the final results to NASTRAN for updated deflection and stress calculations.

Also, a NASTRAN to CODE V conversion utility was generated that maps NASTRAN-produced deflections to motions of CODE V optical components.

All the above was designed to enable external top-level design software (such as the one described in Reference 1) to iteratively evaluate candidate designs for thermal/structural/optical performance as part of a parametric sweep, optimization, calibration, or reliability assessment.

ACKNOWLEDGMENTS

Some of this work was funded by SBIR contracts with the NASA Goddard Space Flight Center. Jeff Bolognese was the technical administrator.

REFERENCES

- 1 B. Cullimore et al, "Automated Multidisciplinary Optimization of a Space-based Telescope," SAE 2002-01-2445, July 2002.
- 2 T. Panczak et al, "A CAD-based Tool for FDM and FEM Radiation and Conductor Modeling," SAE 981577, International Conference on Environmental Systems (ICES), July 1998.
- 3 T. Panczak et al, "Integrating Thermal and Structural Analysis with Thermal Desktop," SAE 1999-01-2126, ICES, July 1999.
- 4 B. Cullimore, "Optimization, Data Correlation, and Parametric Analysis Features in SINDA/FLUINT Version 4.0," SAE 981574, ICES, July 1998.

- 5 B. Cullimore, "Nonlinear Programming Applied to Thermal and Fluid Design Optimization," ECTC/ITHERM, May 2002.
- 6 J. Baumann et al, "Nonlinear Programming Applied to Calibrating Thermal and Fluid Models to Test Data," SEMI-THERM, March 2002.
- 7 B. Cullimore, "Dealing with Uncertainties and Variations in Thermal Design", IPACK2001-15516, InterPack '01 Proceedings, July 2001.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

API	Application Programmer Interface
BFP	Best Fit Plan
CAD.....	Computer Aided Design
CODE V	Optical analyzer from ORA
COM.....	Windows-based communication protocol
FEM.....	Finite Element Modeling
GMM	Geometric Math Modeler (eg., RadCAD)
NASTRAN.....	Structural analyzer from MSC Software
NASCODE	Structural/optical conversion utility from Sigmadyne
NGST	Next Generation Space Telescope
OptiOpt.....	Name of this project/product
RadCAD	Radiation analyzer in Thermal Desktop
RADK	Radiation conductor (network element)
RMS	Root Mean Square
SINDA/FLUINT.	Thermal/fluid analyzer from C&R Technologies
SINDA	Thermal side of SINDA/FLUINT Thermal Desktop
Desktop	CAD-based thermal modeling environment from C&R Technologies
TMM.....	Thermal Math Modeler (e.g., SINDA)