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Parametric Models and Optimization for Rapid Thermal Design

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ABSTRACT

Traditionally, the preliminary thermal design is behind the mechanical and electrical spacecraft design. Many factors contribute to this including a lack of detailed physical characteristics of the spacecraft and knowledge of the distribution of the thermal loads within the spacecraft. Therefore, the thermal design typically reacts to the mechanical and electrical designs. The thermal analyst gets a configuration and then tries to wrap an acceptable solution around it. The analyst relies on years of experience and trial and error to determine the appropriate design cases and create a thermal design. Depending on the experience level of the engineer, several iterations may be necessary to determine the worst-case design points and an acceptable thermal design.

Suppose analysis tools were available that would allow the thermal engineer to rapidly produce preliminary designs and weave the thermal design requirements such as thermal radiator size, preferred radiator location and heat load location into the overall spacecraft design. The result would be a more integrated spacecraft thermal design completed in less time using less of the spacecraft resources.

Advances in thermal analysis software provide the tools for the thermal engineer to perform preliminary analyses more quickly and accurately than ever before. The result is that the thermal engineer can have a greater influence on the spacecraft design process.

INTRODUCTION

This paper takes a look at another approach to the thermal design problem. That is to recast the problem parametrically and use optimization routines to solve for the best thermal design. Instead of modeling a specific thermal design and passing it through the thermal software to calculate temperatures, the parametric model is passed through the optimization routines with a set of constraints to yield a thermal design that meets those constraints. MicroSat Systems Inc. (MSI) is using this parametric approach during the preliminary design phase to quickly determine worst case environments, optimum radiator size/location and preferred heat load placement.

BACKGROUND

Traditional thermal analysis lags the spacecraft design because the design is fluid and changes frequently. Key design features like electrical component placement and structural configuration may take weeks or months to settle. Other component unknowns like mass, volume, thermal dissipation and operational concepts tend to cause a lag in the thermal design. Relocation of components and changes in structural features are not as much of a concern for mechanical analysts because most mechanical designers have a working knowledge of stress and dynamics. They, therefore, take these mechanical factors into account in the design. Fewer designers are fluent in thermal design or analysis and therefore don't fully consider all the thermal implications of the mechanical design decisions that are made. Other unknowns important to a meaningful thermal design include component power levels, payload operations concepts and spacecraft attitude.

Another cause for the lag in thermal design and analysis is that thermal model development can be time consuming especially with data deck analysis tools such as SINDA and TRASYS. In TRASYS, geometry information is often taken from printed drawings. In SINDA, component thermal mass and linear conductors are calculated and input by hand. Both of these tools require a longer time to debug than graphics oriented applications. Geometry based tools have dramatically reduced model development time but design changes still take time to incorporate.

Thermal analysis is also time-consuming because of the way thermal analysts approach the problem. The spacecraft thermal design problem is usually cast in a reactive way. The engineer builds a model of a candidate design solution, solves for temperatures and evaluates the results against a set of requirements to determine if the candidate design is acceptable. If not, the thermal design is adjusted and the process is repeated until all the temperature requirements are met.

IDEAL DESIGN PROCESS

The ideal spacecraft design process is one in which the thermal designer participates from the beginning. From the initial design trade phase, the thermal design is integral with the mechanical and electrical designs. The thermal design considerations influence the structural design and component placement. Ideally, all requirements are known and fixed at the start of the project. Unfortunately, the ideal design process is the exception rather than the rule. More often than not only a portion of the requirements set is known because components haven't been selected or in some cases designed.

The challenge is how to include the thermal design in a spacecraft design process when the thermal design process is typically slow and requires design information that typically isn't available early in a program.

Advances in thermal analysis tools and computer technology have improved the thermal analysis turn around time. Increased computing power has reduced computation time to reach a solution. The graphical interface for the thermal analysis tools has reduced the model creation time. Thermal analysis tools, specifically Thermal Desktop and SINDA/Fluint from Cullimore and Ring Technologies (C&R), have changed to allow the user to look at the design problem from a different point of view. The trial and error approach to determine the worst case condition has been replaced with optimization routines that search out the extreme case. Model unknowns can easily be evaluated parametrically.

SINDA/Fluint has a collection of advanced solution routines that operate through Solver module. It isn't the intent of this paper to discuss the underlying mathematics of those routines, but rather to show how they can be used to improve the thermal design process. A discussion of how these routines work is better presented in papers written by the engineers at Cullimore and Ring Technologies. Section 5 of the SINDA/Fluint User Manual (reference 3) describes the routines available to the user. Table 2 on page 5-18 of the manual 3 has references to papers on the underlying mathematics of the optimization routines.

The Solver routines can perform goal seeking, design optimization, automated model correlation and worst-case scenario definition. Some of the routines involve sweeping the solution space like DVSWEEP, which uses a single variable or DSCANFF, which performs a full factorial scan of a multivariable design space. Both of these routines use equal increments of the design variable. The quality of the solution using these methods is directly proportional to the number of increments in the solution space. Another sweeping routine, DSCANLH, uses a latin hypercube method to sweep multiple design variables. This method has been shown to be more efficient than a full factorial approach, see reference 1. Other routines available in the solver use optimization approach to finding a solution. One thing these routines have in common is that they don't necessarily find the worst case only a poor case. More sample points will return a better solution.

A simple way to look at how the optimization routines work is to think about trying to find the highest point in a particular geographic region when you have no previous knowledge of the region topology and start from an arbitrary location. The boundaries of the region are the design constraints. The only information you have is about where you've already been. By evaluating the slopes you can make your way to the highest point in the region. The problem is that you could reach a local high point that is not the region high point. To minimize the chance of this occurring, a course sweep of the region could be performed first to refine the starting position for the optimization effort.

To enhance the utility of the SINDA/Fluint optimization routines, MSI and C&R developed an interface between Thermal Desktop (or SINDA/Fluint) and Microsoft Excel. At MSI, the Microsoft Excel interface is used as a module in a more complex tool that performs spacecraft subsystem component selection and sizing during proposal efforts. The user of the Spacecraft Wizard tool takes preliminary information provided by a potential customer and populates a spacecraft database. This information includes orbit and mission parameters, data communication requirements and computing needs. The tool determines an initial definition for all the spacecraft subsystems. The "Thermal Wizard" module uses the preliminary information from the database to determine optimum radiator sizes and locations. The Excel to Thermal Desktop interface allows the user to control Thermal Desktop from within the Excel environment. The user can open a model, select a case set, set input parameters, run a case and retrieve output values from the simulation. **Figure 1** shows the Excel input worksheet. The worksheet is simple to use with buttons or pull downs for most items. The user enters the model file name and launches Thermal Desktop. The user then enters the desired case set and the appropriate input parameters. These parameters can be anything defined as a symbol in the Thermal Desktop model. The user then launches the simulation. Upon completion of the simulation, the user can retrieve the results.

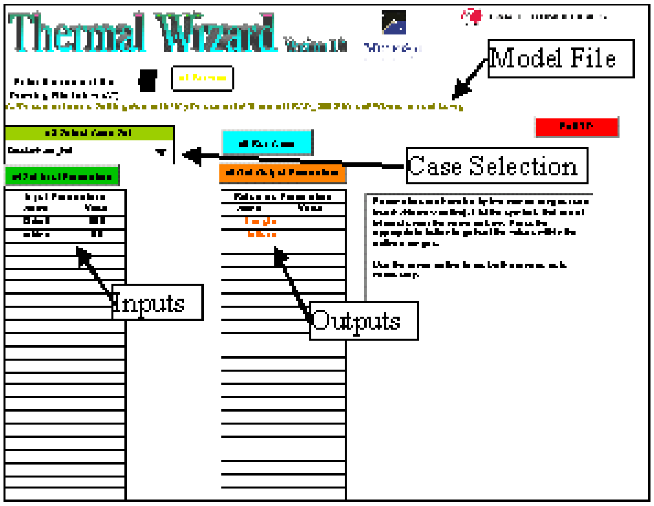


Figure 1 Excel Interface Sheet

RE-CASTING THE THERMAL DESIGN PROBLEM

Utilization of the optimization routines requires the thermal analyst to look at the design problem differently. A simple single variable example is the determination of the worst case thermal environment. Traditionally the analyst modeled a specific orbit and asked if it represented the hottest environment. To answer the question, the analysis must be performed at enough points to describe the solution space. This traditional problem view asked if the selected orbit was hotter than the previous case. Of course the question wasn't asked of the tool but rather of the engineer. The Solver requires the analyst to re-cast the problem to ask what beta angle within a given range yields the maximum heating on the spacecraft. Until recently, thermal analysis tools didn't allow this approach to problem solving. The user defines the desired outcome, what parameters can be modified and the range over which the parameters can be changed.

An example illustrating how the design process has changed is the determination of the worst case hot design environment for a spacecraft in a low-earth circular orbit. Assume the spacecraft orbit beta angle range is –90° to +90°. Over this range some orbits are eclipsed and some orbits are non-eclipsed. The spacecraft is oriented such that one face is always nadir pointed therefore the heat load of five of the faces varies throughout an orbit and with seasonal variations as well.

With traditional tools and processes, the engineer used experience to estimate a starting point and iterated the model in various beta angles to determine the beta angle that resulted in the hottest environment on the spacecraft. Depending on the engineer's knowledge of the solution space contours, this might take dozens of iterations. This is a straightforward situation where the map of the solution space is a single variable. Figure 2 shows a plot of the solution space. There is symmetry about a beta of 0° and peaks at about -68° and 68°. Without knowledge of the solution space, the engineer would need to sweep the entire range to determine the peak. A small number of simulations are inadequate to map the solution. A solution space sweep of five points (0°, ±45° and ±90) would lead the engineer to conclude the maximum around -45° or 45°. Mapping the solution space in 13 steps, 15° increments, results in a closer solution but still not the worst case.

For a single variable solution space, sweeping the range of solutions isn't out of reason. Ten to twenty samples of a single variable with small model to determine the worst case hot design case isn't out of the question. Multiple variable cases, however, can quickly become a daunting task. The number of simulations needed to map the solution space is a function of the number of solution space samples and the number of variables (fn = samples$^{\text{variables}}$). In order to sweep the solution space of a problem with six variables, radiator sizes on a six-sided spacecraft, and three samples of each variable a total of 729 simulation cases are needed. Three samples of each design variable might not be close enough to the optimum solution. Ten (10) samples of each variable and number of simulations jumps to 15,625. You can see that full factorial sweeps of a multivariable design space quickly get become unreasonably large.

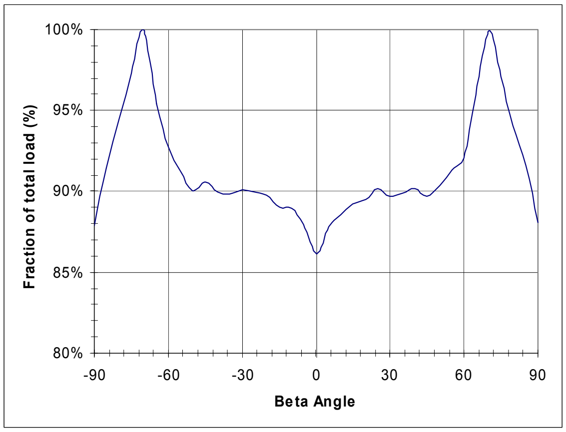


Figure 2 Beta Angle Variation

Using the optimization tools available in SINDA/Fluint, the worst case environment problem is recast to maximize the total heating on all sides of the spacecraft. The design variable is the beta angle and it can vary over the design range (-90° to 90°). The application then takes this model and runs a number of cases to determine the beta angle that results in the hottest environment. The application starts from an arbitrary initial condition and uses slopes to efficiently converge on the solution. Using the optimization routine the solution was obtained in 12 evaluations. The worst case orbit is shown in Figure 3 as viewed from the Sun.

Another key to rapidly creating preliminary thermal design concepts is to start with a model that contains only the essential elements to the problem being solved.

To determine the extreme environment a 6-sided cube could be used. The spacecraft represented in Figure 3 is an example of a simple model. The model consists of six sides and two solar panel representations.

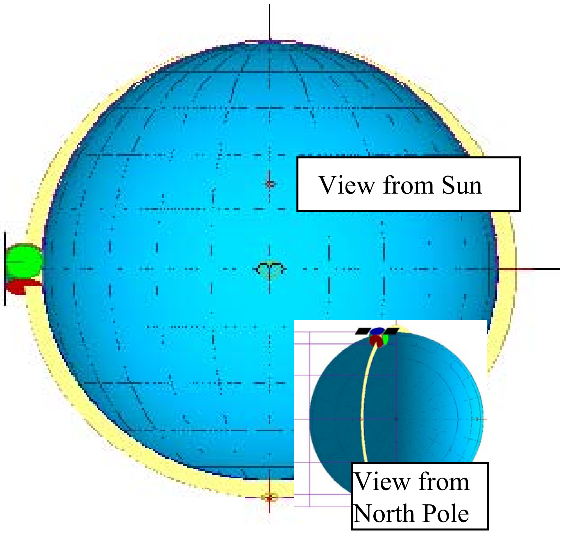


Figure 3 Maximum Heating; Beta 68°

Finding the hottest environment is a simple example and the Solver routines don't have a great time advantage over methods that maps the entire space. The advantage comes from the fact that the solution is the worst hot case rather than just a hot case.

A subtle change to the object of the optimization can make the solution less obvious. Suppose the heating on the nadir face is to be maximized. The worst case environment is less obvious in this case. The engineer must consider the effects of the eclipse time, direct heating and energy from the Earth. The nadir facing deck receives the most energy in a beta 0° orbit. The orbit is shown in Figure 4. This is very different answer than the hottest environment for the entire spacecraft.

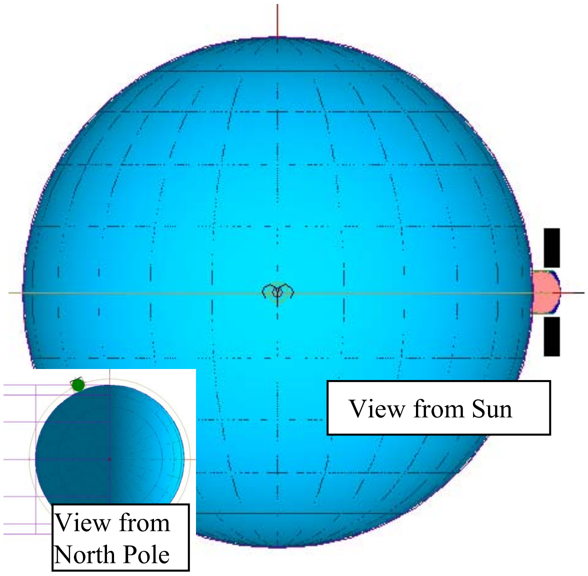


Figure 4 Maximum Nadir Deck Heating; Beta 0°

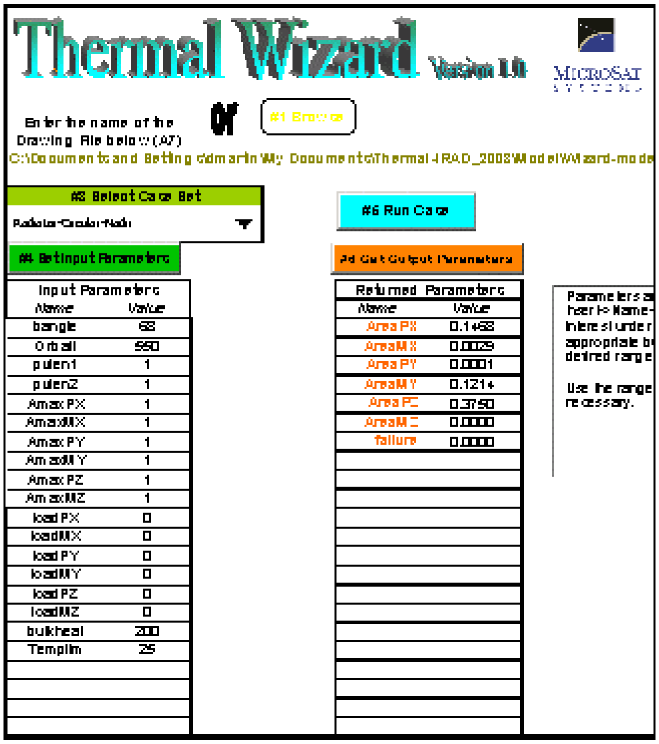
This variation to the original analysis case took just a few minutes to set up and execute using the Solver. This quick response allows the thermal engineer to influence configuration decisions made early in a program.

The ideal spacecraft design process, where all design information is available on the first day of work, is an unrealistic expectation. In reality, on day one, not all the top-level requirements may be firm, the payload suite might be in question, there might be two or three potential launch vehicles and certainly bus subsystems haven't been designed. This doesn't prevent the participation of the thermal engineer in the preliminary design of the spacecraft though. Here is an approach to providing basic thermal requirements to the system in a matter of a few hours rather than days or weeks.

Suppose a design process starts and the only known factors are the spacecraft orbit altitude (550km), the orbit type (circular) and spacecraft orientation (+Z face is Nadir pointing). The estimated orbit average spacecraft power consumption is 200W. The requirements that need to be placed back on the other spacecraft subsystems are thermal radiator areas, radiator locations and component location. Other design features like heater placement, exact set points and temperature sensor quantities and locations can be determined as the design settles out and all the requirements are known.

The first step in the analysis is to determine the hottest environment on the spacecraft. To do this a unit blackbody spacecraft model can be used. This is the six-sided box mentioned previously. This unit spacecraft is used in the optimization model to determine the beta angle that yields the hottest environment on the overall spacecraft. In the optimizer routines the design variable is the beta angle and the objective is to maximize the total heating on the spacecraft. Note that the optimization routines can also minimize the overall heating and determine the coldest case. This could be used later for heater power evaluation. Initially the analysis is performed on an orbit average basis. As more information is known the problem can be modified to optimize for the peak-heating rate on the overall spacecraft or a particular face. For the example, the hottest environment was produced at a beta angle of about -69°. As stated earlier a beta angle of 69° will produce the same heating.

After determining the beta angle for the hot environment, the radiator area and placement can be determined. A unit spacecraft similar to the one used for the beta angle determination is used. This time the beta angle is set for the hot environment and the design variables are the sizes of each of the six faces of the spacecraft. Two other pieces of information are needed to calculate radiator size. The first is the heat load, which has been estimated at 200 watts. The other is the bulk spacecraft temperature. This is a value that will have to be estimated initially. The bulk temperature would generally be somewhat cooler than the component with the lowest operating temperature. This might be a battery or a payload component. Since it's an unknown, the engineer can evaluate the sensitivity of the solution to that value. An initial bulk temperature limit might be 25°C. Figure 5 shows the input sheet for the radiator sizing case. Orbit parameters, solar array size and radiator size limits are input here. The user also has the option to add fidelity to the analysis by applying heat to specific faces if the information is known. The user also inputs the bulk heat and temperature limit.



C:\Documents and Settings\dmartin\My Documents\Thermal-RAD_2003\Model\Wizard-mode

Input Parameters	
Name	Value
bangle	63
Orbalt	550
pulen1	1
pulen2	1
Amax PX	1
AmaxMX	1
Amax PY	1
AmaxMY	1
Amax PZ	1
AmaxMZ	1
load PX	0
loadMX	0
load PY	0
loadMY	0
load PZ	0
loadMZ	0
bulkheat	200
Templim	25

Returned Parameters	
Name	Value
Area PX	0.1458
AreaMX	0.0029
Area PY	0.0001
AreaMY	0.1214
Area PZ	0.3750
AreaMZ	0.0000
failure	0.0000

Parameters a
Other Name-
intere st under
appropriate b
desired range

Use the range
necessary.

Figure 5 Radiator Sizing Input Sheet

The objective of this optimization simulation is to minimize the total spacecraft radiator area while maintaining the bulk temperature of the spacecraft at 25°C. There are six design parameters, the dimensions of each radiator surface. Careful definition of the radiator geometry can simplify the area definition to a single variable. Constraints are placed on the radiator dimensions to prevent unreasonable solutions. For example you might know that there is only one square meter of area available on any one radiator. Then the case is run. The solver manipulates the size of each of the six radiators, within the constraint range, until the minimum is determined while not violating the temperature constraint. The results are retrieved from Thermal Desktop into the Excel worksheet. The analysis results show that for a 200W load the best radiator locations are the Nadir, +X and -Y faces. Components should be placed on these faces first for best thermal performance. As stated above, a sweep of the design space with just three samples of each of the six design variables would take over 700 evaluations. After all these evaluations, the user still isn't certain that the solution is the optimum. Using the optimization techniques, only 125 evaluations were required to find the optimum solution. With a little thought when building the model the heat rejection capability for each of the candidate radiators can be determined.

At the end of this process, which took a few minutes to complete, the thermal engineer has determined the worst case hot environment, an estimate of the required thermal radiator area, the optimum locations for the radiators and the relative heat rejection capability of each radiator. The radiator requirements can then be provided to the engineer responsible for the system configuration for evaluation. As all development processes go, compromises must be made. The reasons for a compromise are varied. Possibly, due to volume limitations, the components cannot be placed in the best locations or portions of a radiator might be obstructed by externally mounted equipment. In these instances, the model constraints can be modified and another analysis iteration made. The revised radiator sizes and locations can be passed on for incorporation into the spacecraft design. Each design iteration can be made in a matter of a few minutes rather than days.

CONCLUSION

Advanced solution features of SINDA/Fluint provide a means for the thermal analyst to make preliminary thermal design calculations concurrently with the mechanical design thereby more directly influencing the spacecraft design. The optimization routines of the Solver module allow the user to quickly find an optimum solution to a problem with several variables. Optimum solutions can be obtained without sweeping the entire design space for all possible cases. This design approach doesn't replace the need for detailed thermal models. It does provide another tool to enhance the collaborative engineering process. As the pressure to reduce design cycle time for spacecraft projects increases, the need for quick effective tools to enhance the design process increases also.

REFERENCES

1. B. Cullimore, "Automated Determination of Worst-case Design Scenarios," SAE 03ICES-004
2. SINDA/FLUINT Advanced Design Modules course notes. Available from Cullimore and Ring Technologies
3. SINDA/FLUINT Users Manual Version 4.6 Available from Cullimore and Ring Technologies

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