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**CONTROL-STRUCTURE-THERMAL INTERACTIONS
IN ANALYSIS OF LUNAR TELESCOPES**

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The Program Development Office is studying the process of concurrent engineering as it applies to the design and development of space vehicles. The research program is specifically charged with developing a process in which the structural, thermal, and active control systems are designed and simulated simultaneously because these subsystems will have a direct effect on mission performance. A small, lunar-based telescope was chosen as a design project about which the Controls-Structures-Thermal Interaction (CSTI) study could formulate the concurrent engineering process and analyze the results. The lunar telescope project was an excellent model for the CSTI study because a telescope is a very sensitive instrument, and thermal expansion or mechanical vibration of the mirror assemblies will rapidly degrade the resolution of the device. Consequently, the interactions are strongly coupled. The lunar surface experiences very large temperature variations that range from approximately -180° C to over 100° C. Although the optical assemblies of the telescopes will be well insulated, the temperature of the mirrors will inevitably fluctuate in a similar cycle, but of much smaller magnitude. In order to obtain images of high quality and clarity, allowable thermal deformations of any point on a mirror must be less than 1 µm. Initial estimates (2) indicate that this corresponds to a temperature variation of much less than 1° through the thickness of the mirror. Therefore, a lunar telescope design will most probably include active thermal control, a means of controlling the shape of the mirrors, or a combination of both systems.

Historically, the design of a complex vehicle was primarily a sequential process in which the basic structure was defined without concurrent detailed analyses of other subsystems. The basic configuration was then passed to the different teams responsible for each subsystem, and their task was to produce a workable solution without requiring major alterations to any principal components or subsystems. Consequently, the final design of the vehicle was not always the most efficient, owing to the fact that each subsystem design was partially constrained by the previous work. This procedure was necessary at the time because the analysis process was extremely time-consuming and had to be started over with each significant alteration of the vehicle. With recent advances in the power and capacity of small computers, and the parallel development of powerful software in structural, thermal, and control system analysis, it is now possible to produce very detailed analyses of intermediate designs in a much shorter period of time. The subsystems can thus be designed concurrently, and alterations in the overall design can be quickly adopted into each analysis; the design becomes an iterative process in which it is much easier to experiment with new ideas, configurations, and components. Concurrent engineering has the potential to produce efficient, highly capable designs because the effect of one subsystem on another can be assessed in much more detail at a very early point in the program.

The research program consisted of several tasks: scale a prototype telescope assembly to a 1 m aperture, develop a model of the telescope assembly by using finite element (FEM) codes that are available on site, determine structural deflections of the mirror surfaces due to the temperature variations, develop a prototype control system to maintain the proper shape of the optical elements, and most important of all, demonstrate the concurrent engineering approach with this example. In addition, the software used for the finite element models and thermal analysis was relatively new within the Program Development Office and had yet to be applied to systems this large or complex; understanding the software and modifying it for use with this project was also required. The I-DEAS software by Structural Dynamics Research Corporation (SDRC) was used to build the finite element models, and TMG developed by Maya Heat Transfer Technologies, Ltd. (which runs as an I-DEAS module) was used for the thermal model calculations. All control system development was accomplished with MATRIX$_X$ by Integrated Systems, Inc.

It was decided that the best approach would be to start with very simple models of low order so that understanding the FEM code and developing the individual elements of the analysis technique would not be hampered with large data files and long computation times. After evaluating the results for each model, additional components would be added to the structure and the cycle would be repeated. Before proceeding to develop simplified telescope models, two test cases were used to establish the operational characteristics of the computer codes for finite element modeling and heat transfer calculations. The first model was a simple cantilevered beam with 20 degrees-of-freedom (DOF), and the second was a planar truss structure with 11 DOFs. The beam model was used to exercise the dynamic analysis modules of the FEM code, and the truss structure was used as a simple example for evaluating the results of the heat transfer codes. These two models were chosen because the dynamics of beam vibration and thermal expansion of truss structures are well known, and solutions for these problems using similar techniques were readily available.

Several problems with the software and its operational peculiarities were clarified. It was discovered that the FEM program was not set up to write the reduced mass and stiffness matrices that are required in the development of the control system. Full-order mass and stiffness matrices were available, but complex post-processing would have been required to eliminate the constrained coordinates. Part of the code actually solved the reduced-order dynamic equations, but the software developers apparently never considered that any users would want to preserve the system equations for future evaluation. Further, the software has a "hard-coded" limit of 500 DOFs. This may be considered adequate for many applications, but when trying to model deflections on the order of a few μm on a large, flexible, thin-shelled structure, more than 500 DOFs will be needed. To fix these problems, several program files were revised and stored for later use; however, working around the DOF limit remains a cumbersome process. In addition, the terminology used in defining boundary condition specifications and DOF definitions was not straightforward to new users of the program. The proper use of these functions was resolved by using the simple beam model and comparing the solutions to known results. The only problem encountered with the TMG solver was its inability to handle higher-order finite elements; parabolic quadrilateral (8-node) elements were used for the mirrors because of the improved accuracy that they can provide. The thermal model, however, simply ignores the mid-side nodes and calculates the temperatures of the corner nodes for each element. A post-processor (included in the TMG module) must then be executed to produce nodal temperatures for the mid-side nodes by linearly interpolating the nodal temperature data at adjacent nodes.

The I-DEAS and TMG software always retains full-order coordinate sets but the control system must use a reduced-order set corresponding to the actual DOFs (i.e. the constraints are eliminated). Therefore, a computer program was needed to transfer the data from one code to the other. Data generated in the I-DEAS format (which includes the TMG results) is stored in no specific order, but the information that must be passed to MATRIX$_X$ has to be processed, and the calculations must be made in a very specific order. For example, it is impossible to reduce the nodal displacements to the reduced DOF set unless the data containing the relationship between the reduced-order and the full-order coordinates is known prior to the operation. Further, investigators have the option of choosing which coordinate set to use for evaluating the results, so the program must be able to accommodate the coordinate set that is chosen. A Fortran code was written to search the I-DEAS data files, select and process the data as specified by the user, and write the data in a format acceptable to the MATRIX$_X$ software.

The next task of the CSTI project was to develop a prototype controller to be used to simulate the mirror shape control. A Linear Quadratic Regulator (LQR) with Integral control (1) was selected because it is a very stable feedback control system, and steady-state errors due to constant inputs or disturbances can be driven to zero. When fully developed, the control system will also include a Kalman Filter to simulate a network of sensors. This type of control system has good response characteristics, and the control and observer gains can be adjusted to simulate different conditions. A control system with these features was written and debugged in MATRIX$_X$ because the software has preprogrammed functions that determine the control and observer gains from the dynamic equations of motion, and a simulation was performed using the truss model as a test case. At that point in the CSTI study, all of the elements required to perform a complete analysis were in place; the next phase was to begin the analysis of the telescope structure.

The initial model that was tested was a free-floating mirror of the correct size and shape but without any additional supporting structure. With this model, the vibrational frequencies would be incorrect, but the thermal loads are quasi-static, and the purpose of this exercise was to proceed through each step in the analysis technique with a representative example. By studying the response of the free mirror, some insight into the placement of sensors and actuators could be gained. Although the mirror was not connected to the structure in any way, a sun shade and lander model, provided by the LUTE project (4), was used to provide more realistic temperature profiles to result from the thermal analysis. A thorough analysis of the thermal loads on the mirror could not be completed prior to the conclusion of the summer program because of the long computation times required to simulate a lunar cycle. Normally, the analysis should cover at least 2 cycles to eliminate any effect of the assumed initial temperatures. Nevertheless, an abbreviated analysis was performed, and it was found that the mirror temperatures can be expected to cycle from -100° C to 52° C during the course of a lunar day (Fig. 1). The data appears to have some errors, particularly near the peak temperatures, but the results should be indicative of the response that can be expected.
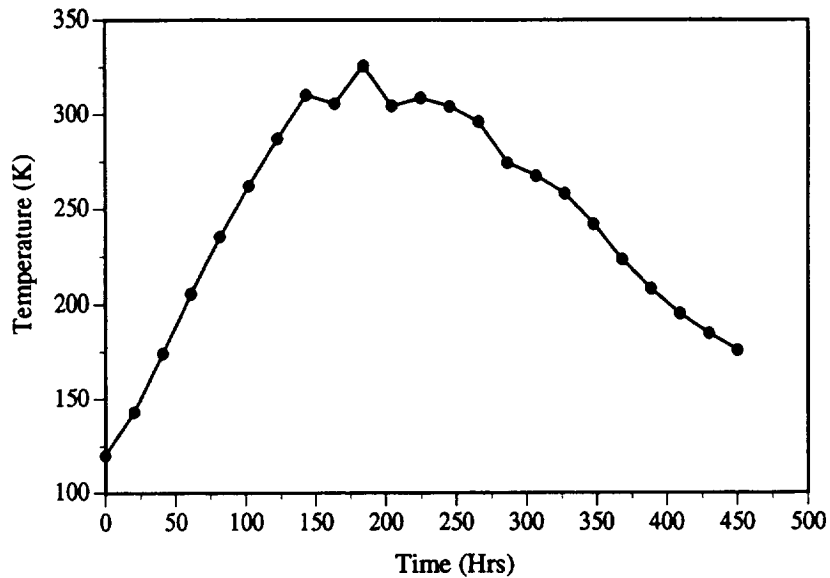
Figure 1. Nodal Temperature Profile

Maximum nodal displacements due to the thermal loads were found to be approximately 550 μm. This is far beyond the allowable deformations, and some form of active thermal control and active shape control will probably be necessary. To test the control system, the thermal loads were applied as step functions; this loading is far worse than would normally be encountered on the lunar surface because of the sudden application of the external loads rather than a smooth, continuous change in conditions. The step disturbance profile could be representative of the thermal loading on the Hubble Space Telescope as it passes through the terminator. Initially, the control system was ineffective, but that was traced to an insufficient number and placement of actuators. Because finding actuator placements that guarantee controllability can be a time-consuming process, the control system was simplified such that actuator placement was not a factor. The observer was eliminated and the actuators, one for each mode, were simulated in "modal space" where an each one can operate independently on an individual mode (3). It should be noted that the simplified controller is essentially the same as the LQR/Integral Controller with an observer; instead of an observer providing an estimated state vector for feedback, the "actual" state vector was used. The use of independent modal controllers, however, is a more serious departure from simulating an actual structure, but any set of actuators which yields a fully controllable system is capable of producing similar results. The control system simulation, shown in Fig. 2, shows that all deformations were eliminated in less than two seconds and the overshoot was very small. These results could be improved by "tuning" the control gains to obtain a more desirable response.

The CSTI study advanced considerably during the ten week period of the 1992 Summer Faculty Fellowship Program. The software used to analyze the control-structure-thermal interactions was tested with representative examples, and some serious problems were resolved. In addition, a computer code was written to interpret the data needed for the control simulations and put the appropriate data in a format that was readable by the MATRIX$_X$ software. Therefore, all of the components necessary for the concurrent engineering approach were developed during the summer program. A simple truss structure was then used as a test case and the CSTI procedure was applied. Finally, an accurate representation of the primary mirror of a proposed lunar telescope was analyzed using the procedure developed during the CSTI study.

Although the description of the procedure may be very succinct, there is a considerable amount of work that goes into each step of the process. The tools are there, but the analysts must determine how a procedure is applied and what accuracy is warranted by the project. Finite element modeling, particularly when highly accurate but low DOF systems are desirable, is a complex field that requires an analyst familiar with the problems that

must be addressed. Similarly, the thermal modeling will require personnel familiar with the thermal environment and the structural configuration. The third component of the CSTI program, controls, also requires a researcher familiar with the trade-offs that must be made and who has some insight into the effect of the performance parameters that must be chosen. Consequently, the CSTI study was developed as a technique by which experts in the very different fields could share results and iteratively refine the design of the subsystems by working more interactively. The software and methods used in the CSTI study can accomplish this goal; for example, the mirror model was constructed and analyzed through one "cycle" of the iterative process in less than one week.
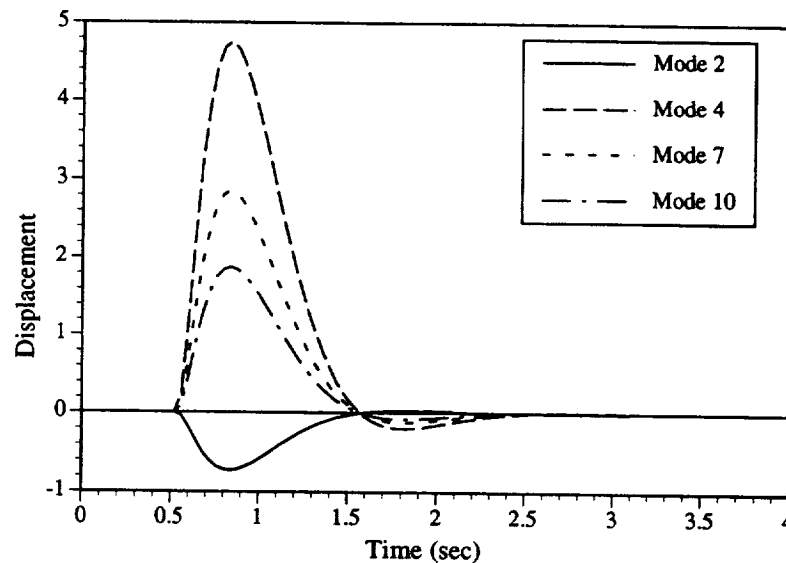

Figure 2. Control System Simulation

The lunar telescope project of the CSTI study has much more work to be done in the future. The foremost task is to develop a more detailed structure. The secondary and tertiary mirrors have to be added to the analytical model and a structure to support all three mirrors must be added. In addition, components such as baffles, optical instrumentation, and support for other subsystems such as power, communications, and command and data handling must be included. The results from this research will be useful in future activities because some knowledge of the displacement patterns was gained from the work completed during the summer program. Additional components of the telescope structure can be added as necessary and the analysis technique can be used to measure the effectiveness of the modifications. Actuator and sensor placement is perhaps the most crucial of the structural issues that must be addressed; actuators produce heat sources, and sensors must be capable of measuring the minute distortions that are to be controlled. Finally, a method of evaluating the optical performance of the structure, and hence the performance of the control system, needs to be included in the simulations. A computer code created specifically for the evaluation of optical systems will be used to determine the telescope's optical aberrations due to mirror deformations, and it should be possible to couple the optical analysis to the control software such that an "instantaneous" evaluation of the telescope performance can be determined.

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