Rapid Opto-Mechanical Design Using Pro/E, MSC/NASTRAN and Code V.

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ABSTRACT:

The mechanical design of Optical systems (Opto-Mechanical Design) is typically concerned with minimizing the impact of the mechanical structure and environments on optical performance. Structurally insignificant loads may induce unacceptable motion and/or distortion into the optical elements, which are summed along the optical path resulting in total image blur and error. Optical system designs are therefore extremely sensitive to mounting configurations and structural dynamic characteristics of the mechanical system. A process for efficient design investigation is discussed that provides rapid system and individual optical element error predictions for mechanical system design. Topics include discussions of fundamental Opto-Mechanical design considerations, Pro/E model modification to facilitate automesh techniques, various automesh approaches using MSC/PATRAN and Pro/Engineer, tet4 vs tet10 element performance and accuracy with MSC/NASTRAN, Line Of Sight (LOS) error predictions, and Zernike polynomial calculations for optical surface aberrations using the MSC/OPOLY utility and Code V.

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INTRODUCTION:

A common concern for mechanical engineers working on packaging and mounting optical systems is the inherent problem of the mechanical structure distorting the optical path and thus the image. Mounting requires physically restraining the optical elements, either mirrors or lenses, by various techniques into a complete mechanical system. Any mechanical load or displacement imposed on the system is to some degree transferred into the optical elements, resulting in distortion of the elements from their baseline shape and position. Typically, optical systems are designed by optics engineers without full accounting of detailed mechanical environmental requirements or mounting constraints such as packaging. Then the element positioning and restraint methods are iterated by the mechanical and optical designers. In addition, for systems subject to high performance requirements, both optical and mechanical as found in IR telescopes, the dynamic environments significantly impact the performance of the unit.

The ability to quickly evaluate various mounting and mechanical system design configurations at the conceptual level, and to provide quantitative design trades between various system configurations is desired. Use of Pro/Engineer (Pro/E) for CAD solid geometry provides rapid generation of complex mechanical systems. Methods to simplify the assemblies into simplified boundary representation solids (b-rep) is necessary to aid in rapid meshing techniques. These simplified b-reps can then be used to generate multiple FE models of the various configurations. Methods for rapidly automeshing these b-rep solids with ‘valid’ tetrahedran models can be performed with Pro/Mesh and/or MSC/PATRAN, and imported to MSC/NASTRAN V70, which can solve reasonably large (> 300,000 dof) solid model static analyses in less than 40 minutes on a current generation UNIX workstation. In addition, specialized tools developed by MSC can be used to provide detailed optical definition of the deformed optical surfaces. The speed and capabilities of this combination of tools makes this process applicable for optical system design investigation during the preliminary design phase.

OPTO-MECHANICAL DESIGN CONSIDERATIONS:

Typical IR telescope optical systems are evaluated on ensquared energy, which is the relative measure of the energy per centered pixel vs. a theoretical maximum. The theoretical maximum is determined by the f/# (f number = effective focal length/entrance pupil diameter), and a selected wavelength. Variables in the system can effect the EE, including distortion in the wavefront, defocus of the image (axial motion of the image), etc. In addition, line-of-sight (LOS) errors summed from the various optical elements cause a shift in the image location from true theoretical location on the image plane, resulting in reported location errors.

For the mechanical design, tight mechanical tolerances are specified for individual components, which must then be evaluated for the entire tolerance stack up. Analytical tools are then used to determine what effect mechanical loads may contribute to the error. LOS error can be calculated for the entire system by summing the effects of multiplying the individual elements tilt (θ) and decenter (δ) by the sensitivity of the system LOS error for each:

$$\mathrm{LOS} = \sum_{i=1}^{n} \left(\frac{\partial (LOS)}{\partial \delta_i} \delta_i + \frac{\partial (LOS)}{\partial \Theta_i} \Theta_i \right) \qquad \text{(Eqn 1)}$$

A further check of the effect of mechanical input on the system is the induced surface aberrations on each element, and the effect of the aberrations on an image. Zernike polynomials are a useful method to describe the surface in terms of separate aberration components, such as piston, tilt, focus, astigmatism, coma, etc. (ref. 1). They are valid for axially symmetrical optical elements, and provide an interpretation of the surface errors by independent terms which contribute to the total rms wavefront error of the image influenced by the optical element. The rms error may then be summed over the entire optical system, resulting in a total system optical wavefront error.

The mechanical restraints, as well as response of the entire system, contributes to the surface error and gross motion for each optical element. Minimizing this effect is the goal of the Opto-Mechanical design.

USE OF MSC/NASTRAN AND MSC/OPOLY FOR OPTICAL DESIGN:

LOS errors can be predicted directly with MSC/NASTRAN, and Zernike polynomials are predicted using DMAP and a utility developed by MSC called MSC/OPOLY.

LOS is a relatively simple process, once the sensitivities of the individual optical elements are obtained. At Raytheon Systems in Tucson, AZ, Code V (ref. 2) is used for optical design, which is able to predict the sensitivities of LOS error to the individual perturbations of each element in tilt and decenter degrees of freedom. The predicted tilt and decenter are obtained from MSC/NASTRAN from individual grids. For relatively small and therefore stiff optical elements, such as small mirrors or refractive lenses, the assumption is made that the element is effectively rigid. A single grid is used, with lumped mass representation of the element, and connected with a rigid RBE2 element to the system mounting points. For larger elements such as primary mirrors, the compliance of the element may significantly affect the response of the system, or have uneven distortion. Therefore, the element is modeled with solid elements, and the optical surface nodal displacements are averaged with an interpolation constraint element, RBE3. These grid points are then output and the appropriate dof's for tilt and decenter are recovered under any loading condition or analysis type.

To allow rapid investigation of various mechanical architectures for the same optical system, a spreadsheet is used to perform the final LOS/G (G-bias sensitivity) error analysis. A LOS/G prediction is a static prediction of the system LOS error under a steady state G load. The results may then be scaled by whatever rigid body acceleration the system is exposed to. Detailed LOS smear accounts for the modal combination of all critical modes, and is typically done in the time domain by exciting the structure with known inputs. For first cut design investigation, this analysis is typically not performed.

As the optical system has been effectively reduced to single nodes representing the optical elements (or averaged results), only the grids representing the optical elements motion are required as output. An alternative method is to write the full LOS equation for the system directly in an MPC, with a scalar point displacement used as the output of the final error. This is appropriate once a baseline design is selected and minimal design changes are expected to the detailed FE model (i.e., no design changes that cause grid number changes to the optical elements and the RBEi elements).

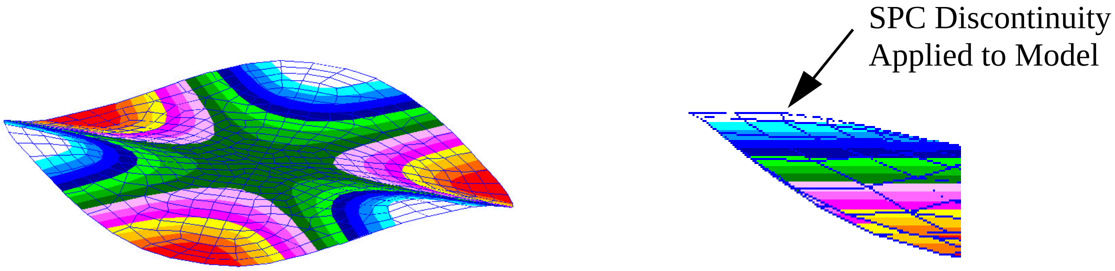
The Zernike polynomials are obtained through a process developed by MSC, using the MSC/OPOLY utility (ref. 3). The approach is to use a set of MPC equations, including the surface nodes of the FE model as input, to generate the Zernike polynomials for the deformed model condition. MSC/OPOLY is a preprocessor 'process' which generates the MPC equations to be included in the full model analysis.

An initial run is made, using an MSC supplied DMAP, which generates a binary output file containing the geometry and area weighting factor information. This run executes only through the geometry creation modules in MSC/NASTRAN, requiring only geometric processing of the model, and does not perform a complete solution. Therefore it is extremely fast, requiring only a few seconds to complete. The output2 binary file is then accessed by MSC/OPOLY, which prompts the user for basic information such as mirror radius, level of symmetry, etc. OPOLY produces an output file which contains the matrix equations and data points used for the surface fit and Zernike coefficients prediction. This output file is included in a final MSC/NASTRAN analysis, and the Zernike polynomials are output along with any other grid displacements desired. No additional modification to the full assembly run is required, other than including the output file from OPOLY and requesting the scalar points as output. Additional requirements for the application to solid models is discussed in the modeling section of this paper.

The Zernike polynomials are imported into Code V, and a fringe and/or deformation plot of the optical surface is created. This information can be used to evaluate the rms error effect on the entire system image, providing feedback directly to the designer on the mechanical system effects on optical quality.

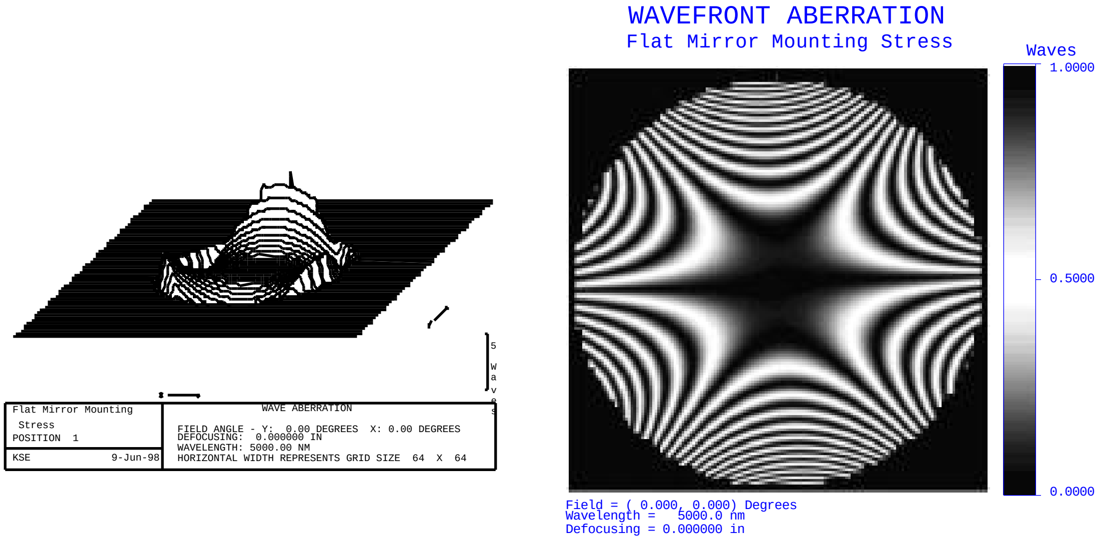
It should be noted that because the Zernike method is a polynomial fit, there are limitations on the accuracy when following complex surface deformations. For example, a simple test was performed with constraints (SPC's) directly on an optical surface to simulate mounting posts near the edge of a mirror. When the resulting Zernike coefficients were imported to Code V, the maximum displacements predicted (in terms of waves on the surface) were approximately 10% greater than the maximum predicted displacements directly predicted by MSC/NASTRAN. Inspection of the grids along a single diameter across one of the constraint 'pads' indicated that the physical displacements from MSC/NASTRAN, as expected, followed the discontinuity imposed by the boundary conditions (Figure 1). Inspection of the Zernike equations shows that the curve fitting techniques used to generate the Zernike coefficients are unable to follow this higher order curve (Figure 2). In hindsight, this is obvious and to be expected. Therefore, the surface deformation was over predicted by the Zernike polynomials when output by Code V.

The error is dependent upon two variables; the slope of the mirror adjacent to the inflection point, and the distance of the mirror edge from the inflection point. The greater the surface slope and ‘overhang’ distance, the larger the error in displacement prediction at the edge. Similar tests have shown errors > 30%, while a test using uniform boundary conditions on the exterior of the mirror surface have provided correlation between Code V and MSC/NASTRAN within 1%.


SPC Discontinuity
Applied to Model

Peak Displacement at Surface Edge = .0010”

Figure 1: PATRAN Displacements For Surface Constrained Plate



Peak displacement at surface edge = .0011”

Figure 2: Code V Displacements For Surface Constrained Plate Using MSC/OPOLY Zernike Coefficients

(Note: The Code V plots shown above are the predictions of the images and wave displacements as if they were measured by an interferometer. Therefore, the displacement of the wave image is 2X the physical deformation of the surface.)

Fortunately, design practice seldom physically restrains an optical surface directly; typically we are mounting on pads to the back side of the mirror component, or on an external position outside the clear (optical) aperture of the surface. The recommendation for applying this method to a design investigation, therefore, is to not constrain any MSC/NASTRAN grids directly on the clear aperture surface, which is likely not the true design intent. If it is necessary to do so, the Zernike predictions and output from Code V are suspect. Whether or not the Code V predictions using the coefficients generated under these conditions represent an accurate model of surface effects is questionable, and will require further investigation.

MODELING:

Pro/Engineer V19 (ref. 4) is used for CAD at Raytheon Systems in Tucson, AZ. Various assembly configurations for a mechanical system can be quickly generated, resulting in a need to rapidly evaluate design A vs B vs C. For concept level evaluation, assumptions can be made that interface joints will behave the same between similar designs, mounting methods will be similar etc. The first order trade decisions are therefore made on the overall system assembly and performance.

In order to facilitate the generation of the FE model, it is desirable to minimize the number of joints and ‘manual’ connections required to be made in the FE preprocessor. Suppression of ‘minor’ features on each part is performed, and then the primary structure and optical elements in the assembly are ‘merged’ into a single Pro/E part.

At this point the user can choose one of two paths. Either the model may be meshed directly using Pro/Mesh within Pro/E, or the geometry may be imported to MSC/PATRAN. Evaluations were made using both meshing capabilities that met success with some differences in performance. MSC/PATRAN V7.5.1 was approximately 2X faster at creating the solid mesh than Pro/Mesh V19, but element quality was roughly equivalent. In addition, applying the same global element constraints, Pro/Mesh generated approximately 2X the number of tetrahedran elements as MSC/PATRAN. Visual inspection of the two meshes (Figure 3) shows that the MSC/PATRAN mesh is more uniform, but detailed numerical inspection using the Element/Verify/Tet capabilities in MSC/PATRAN indicates that they are equivalent. Due to usage constraints on the compute servers at Raytheon, the smaller mesh MSC/PATRAN path was chosen.

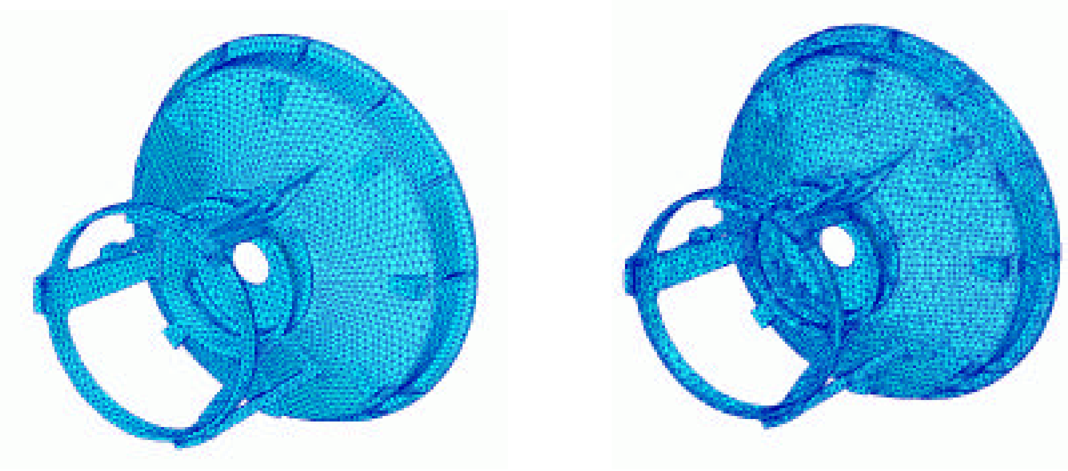


Figure 3: PATRAN V7.5 Auto Tet Mesh vs Pro/E V19 Auto Tet Mesh

MSC/PATRAN can import the part directly as a boundary representation solid (b-rep) to be used for preprocessing the MSC/NASTRAN model. If necessary, multiple Pro/E parts and/or the assembly may be imported and additional geometry created in PATRAN to create a single, continuous FE model; however, this adds complexity to the design investigation. The goal of this process is rapid evaluation, with a turnaround time of less than one day. Once the b-rep is in PATRAN, several options exist for creating the FE model. Tests with MSC/PATRAN V7 were performed to determine which method provided a reasonably accurate model in the shortest amount of time. All testing was performed on an HP C180 with 128 Mb RAM. The fastest method is to use the default ‘hybrid’ method for solid meshing, which generates the solid tets directly from the b-rep. For a relatively complex solid (219 surfaces), the hybrid mesher took less than 10 minutes of real time to mesh 40,000 tet4 elements with 35,000 dof. The state-mesher, or ‘old-PATRAN’ solid mesher, was unable to complete the mesh with the parameters specified, and took over 1 hour to fail.

Another method that has been used successfully to mesh complex solids is the volume fill approach, where the surfaces of the solid are paved with a tri mesh, then the enclosed volume filled with tet elements of the same face order as the surface tri’s (i.e., tri3:tet4 or tri6:tet10). Using this method, the surfaces were meshed with the same global edge length as the hybrid mesher, which took approximately 5 minutes. However, the hybrid mesher was unable to use the same edge length to fill the enclosed volume. Reducing the global edge length for the tet mesh did allow the part to be filled (~ 50,000 tet4 elements, > 40,000 dof), but the total mesh time was ~ 30 minutes.

A definite improvement has been realized however, with V7 of MSC/PATRAN. Prior to V7, the hybrid mesher was unable to provide continuity between surface meshed grids and the b-rep meshed solids grids. In other words, mesh seeding with a surface mesh was not available. With V7, the optical surface may be surface meshed to the desired density for grids to be used for Zernike coefficient recovery, then the solid meshed with the hybrid mesher. This is the recommended approach when Zernike polynomials are desired. Total time including surface meshing 4 optical surfaces and equivalencing coincident grids after generating the solids is only 50% greater than using the hybrid mesher solely, and provides control of the mesh on the optical surface. The total number of solid elements and dofs is equivalent to the solo hybrid mesh.

A limitation to MSC/OPOLY is the inability to use the surfaces of solid elements to describe an optical surface. Therefore a shell element mesh is required on the Pro/E surfaces describing the mirror surface. In addition, we have had sporadic success generating MPC equations with OPOLY, and were unable to identify the cause. However, a standard procedure has been established to ensure success of the process and has resulted in 100% success. Also, this process provides checks at each step before significant resources are wasted on large solid model meshing:

1. Generate surface mesh on optical surfaces, and place elements/nodes into separate groups for later use.
2. Generate surface mesh for entire solid to verify geometry’s ability to be meshed.
3. Using groups for each optical surface, apply pressure loads to define surface normals for MSC/OPOLY, and write out bdf file for single group of surface elements. (Note: although not required in MSC/NASTRAN, a fake property for the shell elements must be created in MSC/PATRAN in order to output correctly)
4. Run MSC/NASTRAN with MSC/OPOLY DMAP to generate geometry op2 file.
5. Run MSC/OPOLY, verifying MPC generation
6. Returning to PATRAN, mesh the solid with tet4’s, including the surface grids for the optical faces.
7. Run sample tet4 including file of MPC equations (be careful of ENDDATA in OPOLY MPC file!) for verification of model and setup.
8. modify tet4 elements to tet10 for solution accuracy.

Tet4 vs. Tet10 DISCUSSION:

It is the author’s and MSC’s opinion that conversion of the tet4 elements to tet10’s is mandatory for most structural applications, including dynamics. Experience by the author while working for MSC and in the automotive and aerospace industries has shown that the linear tet4 is overly stiff (ref. 5). This results in higher natural frequencies and lower stress results. The tet4 is therefore recommended for model checkout, and areas of minimal strain only.

For a sample sensor system, the natural frequencies were shown to drop by > 20% by modifying the element type from Tet4 to Tet10. The density of the mesh, shown in Figure 5, is such that we are not picking up additional fidelity from the increased dofs to recover the fundamental eigenvectors; rather, the difference is due to the formulation difference between the two elements.

As the aspect ratio and Jacobian of the elements created by both PATRAN and Pro/Engineer are often poor in certain areas, it is at the judgment of the engineer to accept or remesh the model. Often, however, the number of poor elements are significantly less than 1% of the total number of elements, and may often be in non-critical regions. MSC/NASTRAN allows the processing of poor elements through the addition of the following commands:

```
NASTRAN SYSTEM(213)=1       $ disables FATAL due to bad element geometry
NASTRAN TETRAAR=1000.       $ opens Tetra element aspect ratio check to 1000.
```

These are extremely dangerous commands, in that they allow elements that are beyond the recommended accuracy to be used in the solution. However, a run can be completed and evaluated for location and numerical accuracy.

A concern in model creation, has been raised using both PATRAN and Pro/Engineer. For complex geometry, both codes have the tendency to create negative volume tet10 elements that MSC/NASTRAN is unable to process, even with the above NASTRAN statements. The midside nodes are placed beyond the element volume created by the straight lines due to the four vertices. Should this problem arise, a simple solution is to mesh the elements initially with a tet4 mesh, then modify the element type to tet10. Due to the relatively dense meshes that are experienced, the loss of geometry association at the midside nodes is usually insignificant to the overall system structural response.

APPLICATION OF LOS PROCESS:

The following example system at Raytheon has a relatively large primary mirror by mobile IR telescope standards. The configuration is shown in Figure 4. Primary design drivers were identified by previous systems to be weight and LOS. For advanced systems, the primary goals are to gain the optical efficiency of the new design, while maintaining or improving the LOS and weight goals from previous programs. In addition, due the large mirror surface, any surface distortions due to mounting are of concern.

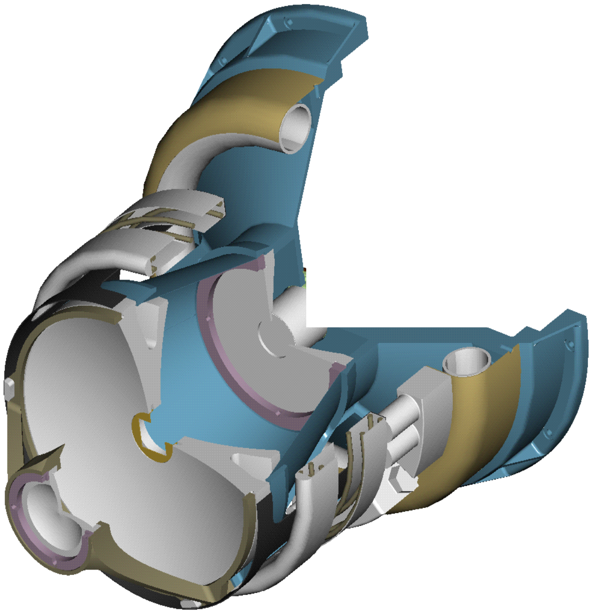


Figure 4: Example IR Telescope Section View

In order to quickly evaluate a mechanical configuration, the Pro/E geometry was reduced to the critical optical and structural components, including the IR telescope housing, primary/tertiary mirror, and the forward structure. All other optical elements were assumed rigid for LOS investigations, and noncritical subassemblies were represented with lumped mass. In Assembly Mode, Components/Adv Utils/Merge Option was used to combine the primary structure and primary/tertiary mirror into a single part file. The 'referenced' parts were copied directly into the base part. All non-structurally critical 'detail' features, such as rounds, spotfaces, thru holes, etc., were suppressed in the new part, and saved to another part filename. This 'merged' part then is used as the basis for all FE modeling, which is independent from the base assembly geometry.

Using PATRAN V7.5, the Pro/E part was imported and the solid b-rep verified. A tri3 surface mesh was laid on the primary and tertiary mirror surfaces, and the nodes and elements placed in separate groups for later manipulation. The solid was then automeshed with tet4 elements, providing continuity on the mirror surfaces with the shell element nodes. After successfully completing a checkout run with the tet4 elements, all tetrahedran elements were modified to tet10's. The final, equivalenced model contains ~ 290,000 dof.

Individual nodes representing the optical elements recovery points were created, and linked to the primary structure using RBE3 for the large mirrors, and RBE2 with CONM2 elements for the small mirrors. The complete model is shown in Figure 5. Total model creation time, beginning with the complete Pro/E assembly, was less than 4 hours.

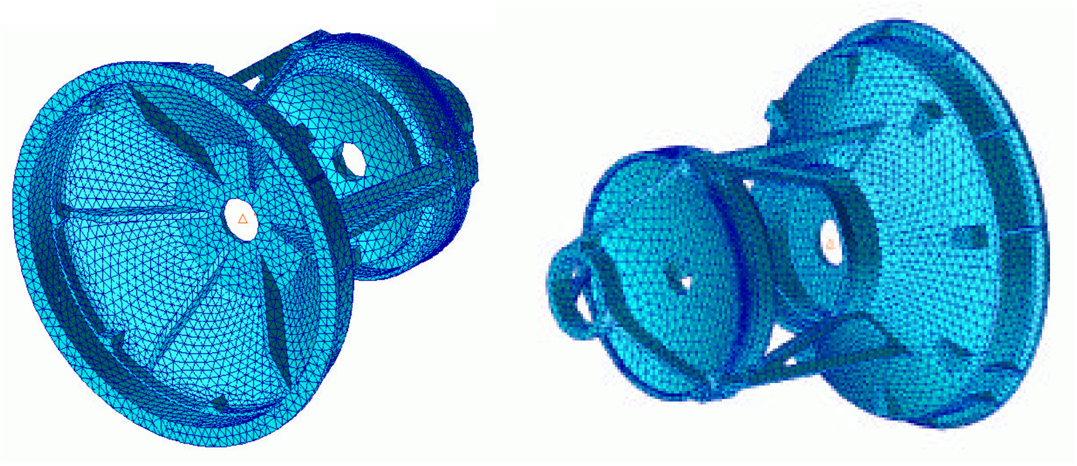


Figure 5: PATRAN V7 Automeshed Telescope Tet Model

For LOS output, only the displacements of the set of optical nodes were recovered.

Optic Motion	***Node Number***	***Contribution to LOS Error (%)***
Primary δ	31002	-69
Primary θ	31002	45
2 Mirror δ	31001	54
2 Mirror θ	31001	-7
Fold Mirror δ	31004	0
Fold Mirror θ	31004	-2
3 Mirror δ	31003	53
3 Mirror θ	31003	28
Transducer δ	99721	-1
Transducer θ	99721	0

Table I: Results For Baseline Configuration to Lateral Static Load

The LOS/G can be evaluated both to the specification requirements for G-Bias error, as well as similar architecture results. Along with the complete model displacement and strain energy plots, this allows the design team to identify modifications to the structure to improve LOS, minimize weight, etc. For this system, the design intent was to concentrate the strain energy for the first bending mode, which is typically the dominant source of LOS error, into the outboard struts and inner cone. The modal strain energy plot for mode 1 is shown in Figure 6, and verifies the system response is as desired.

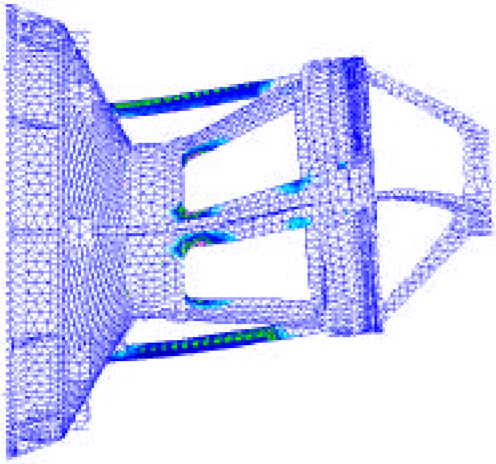


Figure 6: Modal Strain Energy Plot for First Bending

MSC/NASTRAN PERFORMANCE:

The complete model was run on an HP C180 class server with MSC/NASTRAN V70.0. Buffsize was set to 8193. Model matrix size was 292,176 rows (dof), and required less than 14 Mwords of RAM for sparse decomposition. The modal run to 2000 Hz recovered 4 modes, and used less than 23 Mw as reported by HIWATER statistics (sub_dmap MODERS). CPU time was 2583 seconds with 2 decompositions in REIGL, and total disk usage (DBALL/SCRATCH/SCR300) was 3.0 Gb.

The static run cpu time was 2311 seconds, with a HIWATER memory usage of 15 Mwords in sub_dmap SEKRRS. Total disk usage was 2.6 Gb. These statistics are quite impressive and are a critical factor in allowing for rapid FE investigation of complex geometries.

USE OF ZERNIKE COEFFICIENTS:

The fundamental mode is primarily bending; therefore the Zernike Coefficients are expected to show a large tilt term under static lateral loading as a preliminary design check. MSC/OPOLY was used to generate the Zernike Coefficients describing the primary mirror surface error, with minimal fringe error predicted due to the local mounting effects. Figure 7 shows both the Code V 3-D Zernike displacement plot, as well as the fringe error across the surface. All results were as expected. Had the Code V plots exhibited significant fringe errors due to mounting constraints, then design modifications would have been explored to minimize the impact on the surface.

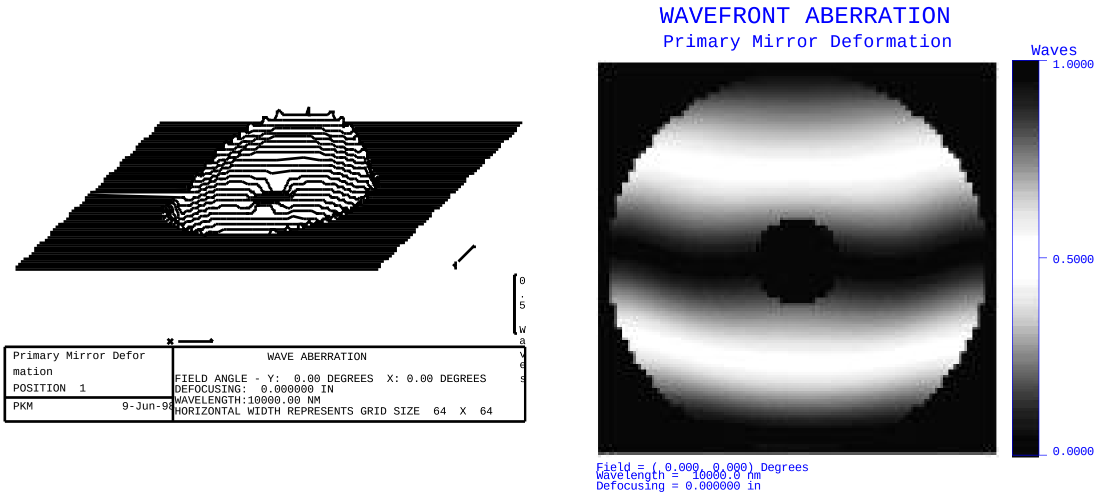


Figure 7: Code V Displacement and Fringe Error

CONCLUSION:

In order to improve design trades on Opto-Mechanical systems, a relatively rapid process involving Pro/E, MSC/NASTRAN, MSC/PATRAN, and Code V has been established. Using this process, fundamental system characteristics, such as normal modes, first order stress results, strain energy distribution(s), LOS errors, and surface deformations can be evaluated in one or two days. Multiple system designs can be evaluated concurrently, providing a significant improvement in first iteration system performance.

There are several fundamental reasons for the ability of this process to be used today. First, the quality of the solid model produced by Pro/Engineer V19 and the translation into MSC/PATRAN V7 is critical. Geometry fixes should be performed in Pro/E, then transferred directly as a b-rep solid into MSC/PATRAN. Second, the solid automeshing capabilities of MSC/PATRAN V7 have significantly improved over the last few releases, both in element quality as well as speed. Finally, MSC/NASTRAN V70's performance on large solid models, both in cpu and memory requirements, allows the solution of complex automeshed models without significant user manipulation through superelements, etc.

All three 'features' have improved to the point of allowing design investigation of this detail to be performed as a 'real-time' design tool during the conceptual system phase. The value added to the design program is realized in an overall improvement of baseline system performance (weight, LOS) prior to detailed design investigation, or providing reasonable performance values during proposal. These are critical for design teams faced with the requirement of reduced cycle time for design and proposal phases of major programs.

Future work in this area will involve correlating Zernike results to actual mirror measurements under load, complete modal surveys of the assembled system, and application of shape optimization techniques linked to the LOS MPC equations to minimize system weight.

ACKNOWLEDGMENTS:

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