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Structural analysis of the space telescope wide-field/planetary camera (WF/PC)

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Abstract

The WF/PC is designed for use on the Hubble Space Telescope (HST). It has complex optics with tight alignment and design requirements. The camera is subjected to various static, dynamic and thermal environments during its ten plus years life. To ensure the camera meets its design objectives and functions properly on orbit, an extensive structural analysis was performed using MSC/NASTRAN. This paper describes the camera, its analysis, and shows the versatility of the finite element method applied to an optical system.

Introduction

The WF/PC is a 622 lb instrument and the main camera for the Hubble Space Telescope. It was designed and built for NASA by the Jet Propulsion Laboratory (JPL) in Pasadena, California. The space telescope will be launched in the space shuttle and placed in earth orbit. It is designed for on-orbit replacement by the shuttle astronauts. A drawing of the camera is shown in Figure 1. The space telescope coordinate system of V1, V2 and V3 are also shown in Figure 1. The V1 direction is the space telescope optical axis and the -V3 direction approximates the WF/PC optical axis. Figure 2 shows the MSC/NASTRAN finite element model of the camera.

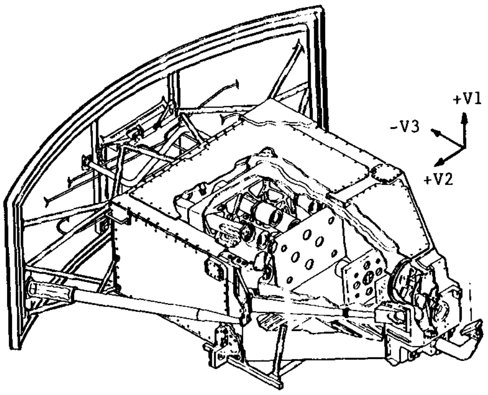

Figure 1. Wide-field/planetary camera.

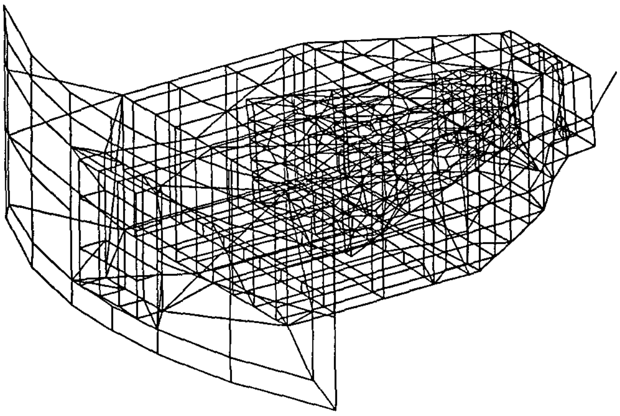

Figure 2. MSC/NASTRAN finite element model.

Optical system description

The wide-field/planetary camera is two complete camera systems. Each camera has its own distinct focal length -- similar to changing from a wide-angle to a telephoto lens. The shorter focal ratio (f/12.9) provides a wide-field of view to capture stars and galaxies. The longer focal ratio (f/30) results in a narrow field of view, to take high resolution pictures of planets and their satellites. The image is obtained by using four solid-state charge-coupled devices (CCDs). A summary of the optical characteristics is given in Table 1.

The light from the space telescope chief ray is diverted into the WF/PC via a pick-off mirror attached to an arm that extends forward from the front of the camera. Inside the camera it passes through filter wheels and arrives at a pyramid mirror which splits the beam into four rays and also rotates to direct the light to either the four wide-field detectors or the four planetary detectors. From the pyramid mirror the light beam is sent forward to fold mirrors which reverses the direction of the light beam back to the relay optics. The relay optics consists of a small, two mirror Cassegrain arrangement.

The Quantum Efficiency Hysteresis (QEH) subsystem was added to allow periodic flooding of the detectors with sunlight which eliminates the problem of the divices charging up and losing their efficiency. This subsystem uses a 45 degree mirror mounted on the radiator, field lenses mounted in light tubes, a periscope arrangement with an objective lens and a flip mirror in the housing to direct the sun light to the detectors.

Structural system description

All the optical elements are mounted on an optical bench which is fabricated from a graphite epoxy and invar for thermal stability. The optical bench is nested inside the housing. The housing provides three attachment points to mount the entire camera into the space telescope. The bench is connected directly to these three attachment points using athermalizing struts. The housing is allowed to change size with temperature without inducing distortions into the optical bench. The housing is made of aluminum and in addition to providing a light seal for the optical bench also contains electronics chassis integral with the structure. An aluminum radiator is attached to the back of the housing by graphite epoxy struts. The CCDs operate at -105 degrees Centigrade and are cooled by thermal electric coolers. Heat pipes conduct heat away from the thermal electric coolers to the radiator where it is radiated to deep space. The radiator also supports Bay 5, which houses the power supplies. The radiator provides four hard points that allows the camera to be picked up by the radiator and installed in the space telescope. During this operation the entire weight of the camera is cantilevered from the radiator. A light baffle is attached to the perimeter of the radiator to prevent stray light from entering the space telescope.

MSC/NASTRAN model

A detailed MSC/NASTRAN model of the housing, optical bench and radiator was developed for initial design and loads analysis. This one model was very versatile in that it was used for static, dynamic and on-orbit thermal distortions. A table of model characteristics is given in Table 2. A picture of the model is given above in Figure 2.

Since only one model was used it had to be capable of pressure and acoustic loads, suitable for thermal loads, representative of the hardware as built, and match the test results for frequency and mode shape.

The choice of elements is straightforward: quads or triangles for plates, shear panels where required, bars and beams for struts, arms, stiffeners or longerons, rigid elements for structural attachment interfaces and where required for proper structural simulation. Mass was modeled by lumped masses and as distributed masses by the density option on the material cards. The weight break down of components follows:

Optical bench:	223 lbs
Radiator:	102 lbs
Housing:	269 lbs
QEH:	25 lbs
Total:	619 lbs

The model was given an extensive battery of quality checks which are summarized below and are described in detail in Reference 1.

- Model matches hardware for primary structure
- Input data checkout run (RF24D32)
- Complete plots and schematics of the model
- 1G XYZ gravity
- Eigenvalue with rigid body check
- Thermal checkout
- Equilibrium check

Structural analysis requirements

The model was used to generate internal loads, displacements and natural frequencies for the following project requirements:

- Ground handling and transportation loads
- Space shuttle lift-off and landing loads
- Installation condition (camera cantilevered from Bay 5)
- Light baffle loads on radiator
- Internal pressure
- Housing first resonance: above 30 Hz
- Optical bench resonance: above 40 Hz.

Dynamic Analysis

The model was used to calculate the normal modes of the system to ensure the frequency requirements given above would be met. A description of the first five modes follows:

Mode 1: 30.5 Hz - Radiator and housing bounce
Mode 2: 35.2 Hz - Radiator yaw
Mode 3: 40.0 Hz - Pick-off mirror arm yaw
Mode 4: 48.1 Hz - Optical bench bounce
Mode 5: 61.4 Hz - Radiator yaw

Since the model already existed for static and dynamic analysis it was determined to use this model to predict test results which would be an aid for planning and monitoring the sine sweep, random vibration and acoustic test that the camera would undergo. MSC/NASTRAN was used directly for the sine sweep analysis and ARI RANDOM, a NASTRAN post processor, was used for the random and acoustic analysis. The specifications for these tests are given in Table 3 and Reference 2 gives the details of the random vibration and acoustic analysis.

Test support philosophy and procedure

The test response prediction effort was used to support the dynamic testing of the entire system. Since the actual flight hardware was used for the test program and the tests were performed to protoflight levels (levels higher than anticipated in flight) with no precursor test article, it was important to be able to assess preliminary results as the test was in progress to protect the camera from over test.

The MSC/NASTRAN model and associated dynamic anlyses were used to predict responses for all levels of testing. This resulted in g levels at points on the model corresponding to accelerometer locations and element member forces from the model were converted to stresses by hand calculations. Margins of safety (M.S.) were obtained for those predictions and are directly related to test g levels i.e., it is known what level of a given channel produces zero margn of safety. For strain gages, stress and margins of safety were related directly to strain gage readings. Data could now be organized into tables giving the response, margin of safety and the specific page of analysis for each data channel (see Table 4 for example).

The "quick look" method was used during the random vibration and acoustic test programs. These test programs called for two lower level runs to be made before achieving the qualification levels. After a lower level run was made critical data channels were plotted. A "quick look" was made comparing these levels to pretest predictions and margins of safety. If a lower level run showed responses higher than predicted, then the margins of safety were reviewed to access the risk prior to going to the next level. This process was continued until all tests were complete. The "quick look" method proved successful for supporting the test with the high level of confidence needed to ensure the safety of the camera.

The test response predictions proved useful for pretest planning in selecting locations of accelerometer and strain gages and of limiter locations. The priority of which channels would be limiters and the values for the limiter channels were also selected by pretest predictions. The philosophy was to set the limiters to the predicted value for that level of testing. If that level caused a test abort, to see what value the limiter could be safely raised to, a review was made using the "quick look" method. Again the "quick look" method, based on pretest predictions and planning, proved successful for raising limiter values with confidence and still protecting the hardware.

Test prediction versus test results

The test predictions and test results are given in g's rms. This rms value is defined as the square root of the value of the Power Spectral Density (PSD) integrated over the frequency. The rms analytical prediction can be compared to the rms test results by integrating the response to 300 Hz. Since only normal modes below 225 Hz were used in the analytical model no significant predicted responses exist above this arbitrary value of 300 Hz. Hence in Table 5, the test response PSD is integrated to 300 Hz to obtain the grms value for comparison to the analytical prediction. For strain gages only the full integration of the test measurements were used (0-2000 Hz). This is due to the fact that strain gages were self-filtering at the higher frequencies. The comparison of predicted versus test values presented in Table 5, while not within the traditional engineering tolerance, have shown to be adequate to fulfill the objectives of the analysis as given above.

Updating the model to match test results

After the dynamic testing the model was updated to match the test results for frequency and mode shape. Data from the random vibration and .1 g sine sweep tests was reduced to provide natural resonances and phase relationships. Modes were identified for the major subsystems (housing, radiator and optical bench) not only by mode shape but by kinetic and strain energy content for each mode. The MSC/NASTRAN model was then modified to approximate the test results. The element strain energy option in NASTRAN was used to identify the elements for a given mode that may need some stiffness adjustment. Kinetic energy distribution for each mode was achieved by a special modification to MSC/NASTRAN (see Reference 2 for description of this procedure) to print out the kinetic energy of each grid point. A FORTRAN program was used to sum up the kinetic energy for each subsystem and this distribution was compared to the test results and is given in Table 6.

Optical Analysis

The WF/PC has very tight alignment and stability requirements. The objective of the analysis was to determine the effect on the optics due to one g gravity release, whereby the optics are assembled and aligned in a one g field, and when taken into orbit relax to a zero g state. The other objective was to determine the effects on the optics due to temperature changes on orbit during a long time exposure (4 hours) and also due to a 1 degree Centigrade change at either of the three attachment points. The criterion for the analysis was less than 1/10 pixel displacement of the image in the plane of the CCD detectors (1/10 pixel = .00006 inches). The optical elements considered were the pick-off mirror, pyramid mirror, fold mirrors and relay optics.

Optical transformations were derived by the optical engineers. Each transformation represents the displacement of the light beam in the plane of the detectors due to a unit motion of an optical element. There are 8 channels (4 wide-field and 4 planetary) and two directions of interest per channel for a total of 16 optical parameters monitored. The total number of transforms used was:

Pick-off Mirror: 5 x 2 x 8 = 80
Pyramid Mirror: 4 x 2 x 8 = 64
Fold Mirror: 4 x 2 x 8 = 64
Relay Optics: 4 x 2 x 8 = 64
Total: 272

From the model, five displacements were used for the pick-off mirror and six displacements each for the pyramid mirror, fold mirrors, and relay optics for a total of 23 model displacements used. To simplify the analysis, motion of the pyramid mirror, fold mirrors and relay optics was represented by the motion of one point on the respective bulkheads, to which these elements are mounted. Pick-off mirror displacements were taken from a grid point in the model that directly represented the mirror. A similar procedure was used to evaluate the performance of the QEH optics.

Initial evaluations were made by multiplying the model displacements and the optical transforms by hand. The intent was to automate the procedure by putting the optical transforms directly into the model as a set of linear equations by using the multipoint constraint (MPC) feature of NASTRAN, and then reading the image displacement on the CCDs directly from the model output for the conditions described. Project limitations of time did not permit the step, however this procedure is described in detail in Reference 3. The results showed the following:

17 pixels: 1g gravity release
.2 pixels: 4 hour exposure
.02 pixels: 1 degree Centigrade change at attachment points

The 17 pixels from the 1g gravity release, although greater than 1/10 pixels, was determined to be within the bounds of the overlap margin used to combine the four CCDs into one image. A review by the optics engineers determined that the .2 pixel displacement from the four hour time exposure was no substantial problem. A similar analysis was performed for the QEH subsystem and the results showed no problem whatever for 1g release or on-orbit temperature changes. The MSC/NASTRAN model proved to be an effective tool for predicting optical performance during the design phase or prior to operation of an optical instrument.

Video documentation of the structural analysis

The project office requested that the major disciplines document their efforts on the WF/PC on videos done at JPL's studio. The video for the structural analysis of the camera was actually broken down into three separate videos: "The Model", "The Analysis", "Testing and Results". With the aid of photographs, colored art work and simple studio techniques complex parts of the finite element model were easily explained in a straightforward and easily assimilated manner. Since this format was more relaxed and less formal than written reports it was possible to explain parts of the analysis and testing in a more candid manner and cover some topics which would have been omitted in a formal report but which may be important in the future.

The video proved to be a valuable resource to the project office and was used to indoctrinate new personnel to the project. In addition, several full sets (43 videos) were sent to outside agencies involved with the space telescope project.

Conclusion

The MSC/NASTRAN model of the WF/PC proved to be a valuable tool not only for traditional stress analysis, but also by extending its capability it provided additional information for test support and for determining optical performance.

Acknowledgments

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Table 1. Optical characteristics

Characteristic	Wide-field	Planetary
R-ratio	12.9	30
Composite angular field of view	2.67 x 2.67 arcmin	68.7 x 68.7 arcsec
Resolution	0.12 arcsec	0.043 arcsec
Number of CCD cameras	4	4
Number of pixels	1600 x 1600	1600 x 1600
Wavelength coverage (Angstroms)	1200 to 12,000	1200 to 12,000
Number of filters	48	48

Table 2. Model characteristics

Number of grid points	748
Number of static degrees of freedom	4,285
Number of finite elements	1,475
Cbar	705
Cbeam	2
Celas2	6
Cquad	438
Cshear	101
Ctria3	223
Number of mass degrees of freedom	2,803
Number of dynamic degrees of freedom	168
Modes retained	25
Upper frequency	220 Hz

Table 3. Dynamic test summary

.1 g Sine sweep

- Single axis input in a direction normal to the mounting plane
- Used to determine first natural frequency
- 5 to 150 Hz up and down sweep
- Used as post protoflight random vibration signature test

Random vibration

- Single axis input in a direction normal to the mounting plane
- Three levels 20 to 2,000 Hz
  - Down 6dB from flight acceptance level
  - Flight acceptance level (1.80 grms)
  - Protoflight level (2.85 grms)

Acoustic test

- Three levels 31.5 to 10,000 Hz
  - Down 6dB from flight acceptance level
  - Flight acceptance level (143 dB overall)
  - Protoflight level (147 dB overall)

Table 4. Sample table of test predictions and margins

Channel	Direction	Location	grms	M.S.	Report
A31	V1	Housing	3.5	1.5	21/p. 6
A32	V2	Housing	2.1	2.3	21/p. 7
A33	V3	Housing	3.1	.8	21/p. 7
A39	V1	Radiator	3.2	1.3	14/p. 5
A40	V2	Radiator	1.8	2.2	14/p. 6
A41	V3	Radiator	1.0	5.2	14/p. 9

Table 5. Selected test responses vs. predictions (protoflight levels)

		Random vibration response (grms)			Acoustic response (grms)		
Direction	Location	Prediction	Test 300 Hz Limit	Test 2,000 Hz Limit	Prediction	Test 300 Hz Limit	Test 2,000 Hz Limit
V1	Bay 5	4.3	2.4	2.5	1.6	1.1	1.9
V2		1.4	1.4	1.6	1.6	.8	1.5
V3		2.9	1.6	1.7	1.5	.8	1.7
V1	Radiator corner	3.6	2.7	2.9	3.5	2.0	3.1
V2		4.0	2.0	2.0	3.3	1.3	2.3
V3		9.3	1.2	1.3	8.5	7.1	7.3
V1	Filter mechanism	2.1	3.5	5.7	.8	1.0	2.7
V2		3.0	1.5	4.7	2.5	1.0	2.5
V1	Relay optics bulkhead	3.3	1.2	1.3	.6	1.0	1.1
V2		3.1	.8	1.0	.4	.5	.5
V3		2.7	1.1	1.4	.6	.4	.5
		Random vibration strain data (rms)			Acoustic response strain data (rms)		
Direction	Location	Prediction	Test 300 Hz Limit	Test 2,000 Hz Limit	Prediction	Test 300 Hz Limit	Test 2,000 Hz Limit
--	Optical bench strut	325 lb	--	209 lb	37 lb	--	44 lb
--	Pick-off mirror arm	134 in-lb	--	218 in-lb	20 in-lb	--	155 in-lb
--	Radiator truss	38 lb	--	40 lb	61 lb	--	30 lb

Table 6. Model and test modal comparison

Mode	Item	MSC/NASTRAN model		Vibration test	
		Freq. (Hz)	% K.E.	Freq. (Hz)	% K.E.
1	Radiator Housing Optical bench	30.5	V1 = 61 V1 = 21 V1 = 1	29-30	V1 = 50 V1 = 10 V1 = 18
2	Radiator	35.1	V1 = 6 V2 = 43 V3 = 36	34	N/A
3	Optical bench	40.0	V1 = 38 V2 = 19 V3 = 5	41-42	V1 = 43 V2 = 16 V3 = 7
4	Optical bench	48.1	V1 = 22 V2 = 5 V3 = 2	51	V1 = 23 V2 = 39 V3 = 16