Cryogenic mirror mounts for use on JWST's NIRCam instrument

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ABSTRACT

This paper describes the design of the compact, lightweight, and athermalized Pick Off Mirror and Mount as well as similar mounts for other NIRCam fold mirrors, including the Focal Plane Assembly Fold Mirror Mount. Structural and thermal analysis as well as actual prototype testing is also described.

Keywords: JWST, James Web Space Telescope, NIRCam, mirror, mount, athermal, cryogenic

1. INTRODUCTION

James Webb Space Telescope (formerly Next Generation Space Telescope, or NGST). The JWST possesses an aperture with ten times the collecting area of the Hubble Space Telescope. JWST has a broadband IR capability that, from the vicinity of Lagrange 2 (nine hundred thousand km from earth), will allow a view into the distant history of galaxy formation. The instrument will be required to furnish high-quality infrared imaging performance while operating in a challenging cryogenic (37 Kelvin) space environment over a 5-year (10 year goal) mission.
Two optical modules, mounted back to back, comprise the NIRCam instrument. Each module (Fig. 1) contains a short wavelength (SW) and long wavelength (LW) optical path. The instrument will be mounted to the Integrated Science Instrument Module (ISIM) of the spacecraft by kinematic mounts.
NIRCam is an IR imaging instrument that makes up part of the science instrument complement of the

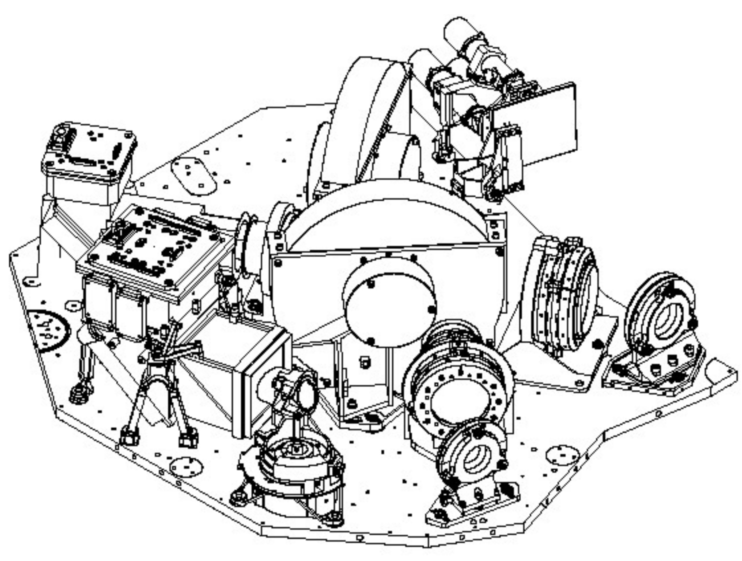

Figure 1. NIRCam Module A (shown without baffles)

2. PICK OFF MIRROR ASSEMBLY

Each module includes one Pick Off Mirror (POM) which is mounted to the Focus and Alignment Mechanism (FAM) (Fig. 2). The Pick-off Mirror is a mounted, spherically concave mirror that reflects the starlight from the JWST optical telescope element (OTE) into the NIRCam SW and LW imaging channels.

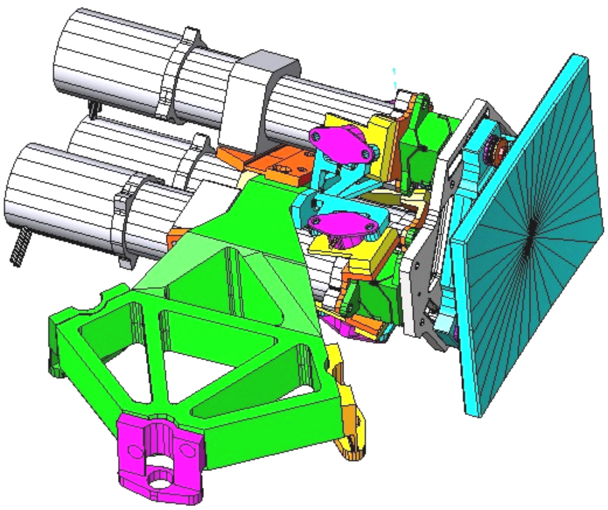

Figure 2. Focus and Alignment Mechanism

The POM (Fig. 3) is made from fused silica. It is a monolithic glass structure consisting of a nominal 6mm face sheet, a hub, three tabs, and a cutout in the central hub.

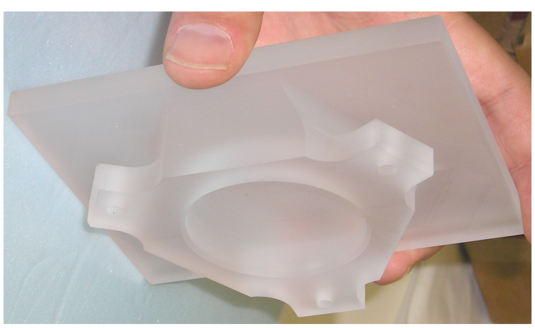

Figure 3. Pick Off Mirror (Uncoated)

The pick off mirror assembly (POMA) incorporates a titanium delta plate with integral flexures to interface between the POM and the FAM. The flexures on the delta plate each provide a single degree of freedom, allowing relative radial expansion/contraction of the low dl/L fused silica mirror and the high dl/L titanium plate, while minimizing stresses in the two parts. As a secondary benefit, the flexures allow pre-defined radial alignment adjustability between the mirror holes and the holes in the plate. In three places, titanium shoulder bolts secure the delta plate to the mirror. A close-fit diameter titanium sleeve fits over the shoulder of the bolt and determines a specific preload using a stack of belville washers (Fig. 5). The belville washers are confined between two flat washers, one titanium and the other PCTFE. Since its modulus is lower than the modulus of titanium, PCTFE is used to reduce contact stresses on the fused silica.

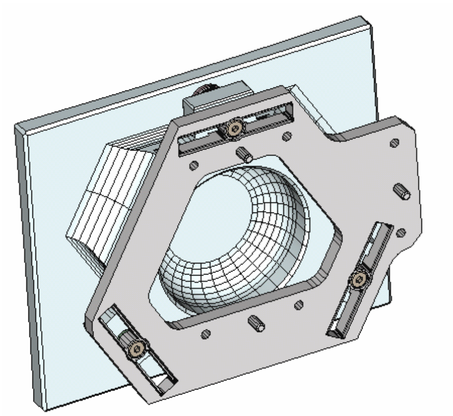

Figure 4. Pick Off Mirror Assembly

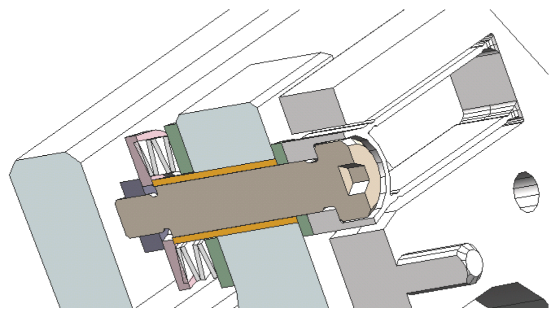

Figure 5. Cross Section of Clamp Configuration

The design must accommodate the cryogenic environment as well as a limiting mass and envelope size. The POM is lightweighted approximately 40%, with the mounted optic being only 30mm thick from front to back. The lightweighted mirror has a central hub and an additional cutout to eliminate additional mass. This novel approach to optic and mount construction results in a compact and nearly athermal mount design, allowing the mount surrounding the mirror to shrink while the low expansion fused silica mirror changes dimension very little.

2.1 Pick off mirror assembly analysis

The mirror and delta plate were modeled with second order tetrahedrons (Fig. 6). The surface of the mirror is meshed with a thin layer of shell elements in order to extract 5 degree of freedom displacements for surface distortion analysis (solid elements have only 3 degrees of freedom). Interfaces were connected with rigid bar elements. Last, the flexures on the delta plate were modeled with shell elements. The delta plate attaches to the FAM at three locations with one pin and two fasteners at each location. The FAM has kinematic flexures in the linear actuators, which allow each FAM interface to take axial and tangential loads only. Bending, torsion, and radial degrees of freedom are free. Boundary conditions were applied to the interfaces such that the pins take tangential shear load and the fasteners take axial load only. All of the models presented in this paper were meshed in I-DEAS Master Series version 9 and exported through a translator for MSC/NASTRAN version 2001. Analysis runs and model checks were performed with NX/NASTRAN version 2.0.

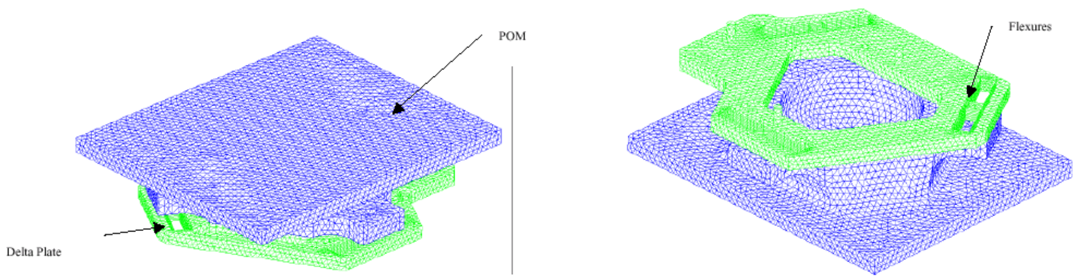

Figure 6. Finite Element Model

Distortion Load Cases:
The following load cases were evaluated for their effects on the mirror surface distortion:

- **Cool Down**: Cool down from room temperature (293K) to cryo (35K), which results in a 1.4 Newton flexure force.
- **1g in X:** Lateral gravity sag.
- **1g in Y:** Lateral gravity sag.
- **1g in Z:** Axial gravity sag.
- **Fastener Preload:** 68 Newton preload in fasteners attaching mirror to delta plate flexures.
- **Flexure Preload:** 127 micron enforced displacement at flexures due to an assembly tolerance that results in a 4.6 Newton flexure force.
- **Side Thermal Gradient:** A side-to-side operational thermal gradient of 0.25K.
- **Top Thermal Gradient:** A top-to-bottom operational thermal gradient of 0.25K.
- **FAM Load (6 cases):** FAM flexure induced distortion on delta plate when FAM is driven to 1-degree tilt with 4.0 N-m/rad FAM flexure stiffness.

Table 1. Modal Analysis Summary

			Modal Effective Mass					
Mode	**Frequency (Hz)**	**Description**	**ux**	**uy**	**uz**	**rx**	**ry**	**rz**
1	454	Shear	29%	11%	10%	3%	11%	0%
2	512	Shear	21%	57%	0%	0%	0%	8%
3	677	Despace	27%	7%	50%	2%	13%	1%
4	846	Tip/Tilt	6%	1%	6%	8%	36%	31%
5	891	Tip/Tilt	14%	1%	17%	22%	20%	18%
6	1032	Tip/Tilt	0%	20%	0%	43%	4%	40%

The modal analysis results (Table 1) show that the assembly is very stiff and the first mode frequency of 454 Hz is well above the 150 Hz goal. The following surface distortion summary (Table 2) shows a nearly athermal behavior. All of the predicted errors (with the exception of gravity, non-operational) are on the single digit nanometer rms level.

Table 2. Surface Distortion Summary

Source	Predicted Error (nm RMS)	Allocation (nm RMS)
Cool Down (1.35 N Flexure Force)	2	17
1g Sag in X	20	22
1g Sag in Y	16	22
1g Sag in Z	15	22
Mechanical Preload (68 N Fastener Force)	2	20
Mechanical Preload (127 micron Flexure Displacement)	7	20
0.25K Side to Side Thermal Gradient	0	5
0.25K Top to Bottom Thermal Gradient	4	5
FAM Flexure Load at Flexure 1 (.1 N-m)	3	TBD
FAM Flexure Load at Flexure 2 (.1 N-m)	3	TBD
FAM Flexure Load at Flexure 3 (.1 N-m)	0	TBD
FAM Flexure Load at Flexure 1 (.1 N-m)	1	TBD
FAM Flexure Load at Flexure 2 (.1 N-m)	1	TBD
FAM Flexure Load at Flexure 3 (.1 N-m)	0	TBD

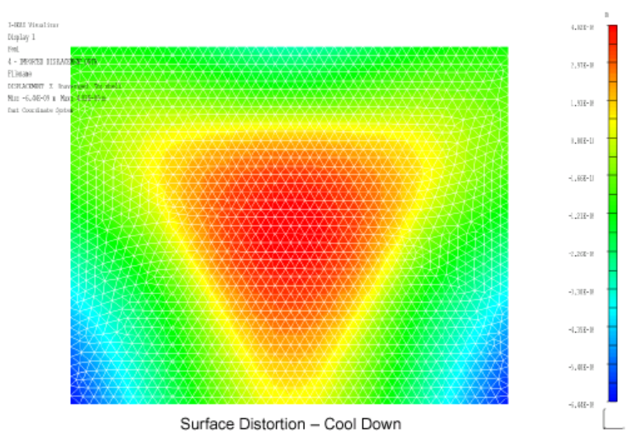

Figure 7. Cool Down Distortion (< 2nm full scale)

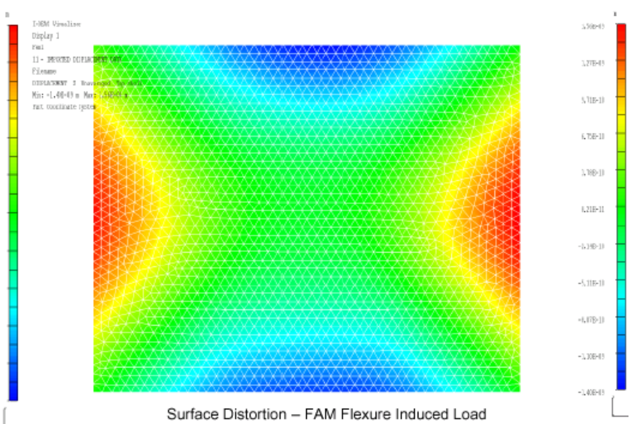

Figure 8. FAM Flexure Induced Load (< 2nm full scale)

2.2 Pick off mirror prototype

A POMA prototype was manufactured, assembled, and tested in order to reduce risks and build confidence in the areas of manufacturing, launch environment performance, and thermal environment performance. Nu-Tek Precision manufactured the prototype POM. The prototype assembly underwent a random vibration test to proto-flight level (14g_{rms} for one minute per axis). The assembly was then placed in a cryogenic vacuum chamber and the wavefront was measured near operating temperature. The assembly was thermally cycled three times and the wavefront was measured after each cycle. At the time of publication of this paper, the results of the vibration and cryogenic testing were not yet available.

3. SHORTWAVE FOLD FLAT MIRROR ASSEMBLY

Each of the two NIRCam imager modules requires one Shortwave Fold Flat Mirror Assembly, which is mounted to the Optical Bench Assembly (OBA). The Shortwave Fold Flat (SWFF) is a mounted, flat mirror that reflects the starlight from the SW camera triplet subassembly toward the SW focal plane assembly (FPA).

In addition, the First Fold Mirror (FFM) Subassembly consists of a mounted mirror that redirects the starlight from the POMA into the collimator lens triplet and the rest of the NIRCam Instrument. The SWFF and the FFM have similar mounts, so only the SWFF mirror assembly will be discussed in this paper.

Like the POM, the SWFF mirror is made of fused silica. It is a truncated circular mirror (circle with a flat). Behind the facesheet, the mirror has a geometry similar to the POM. However, the SWFF is not mounted to a mechanism. It is mounted to a bracket interface (Fig. 9) that attaches directly to the OBA. Also, because of volume restrictions, the mirror mount position was moved in relation to the mirror attachments. The mount consists of three parts that fasten together around the mirror. The mirror is assembled onto the bottom "horseshoe" shaped piece and then the top mount locates precisely with shear pins and fasteners. Preloaded shoulder bolts slip through the mirror and bottom out/thread into the flexured mount (Fig. 10). The mount rests on top of two balls and a series of preloaded adjustment/set screws for precision tip adjustment. This design is even more compact than the POM design (in the direction normal to the mirror surface) since the mount surrounds the center of gravity of the mirror.

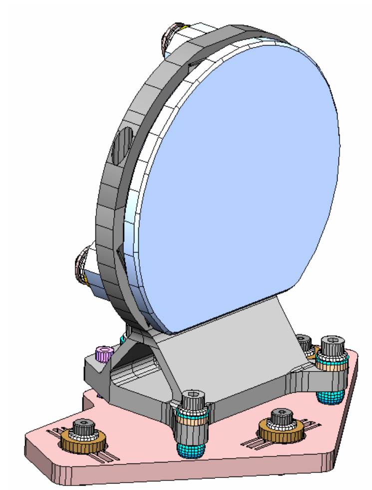

Figure 9. SWFFA

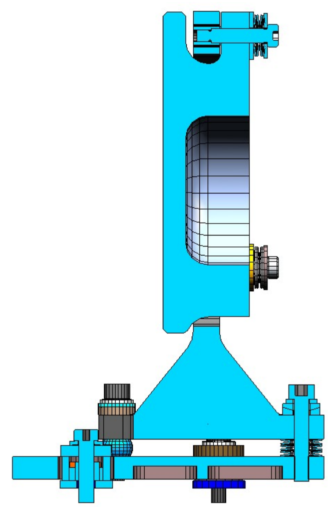

Figure 10. SWFFA Cross Section

3.1 SWFF mirror assembly analysis

The NIRCam Short Wave Fold Flat Assembly (SWFFA) is analyzed for gravity sag, thermal distortion and effects of mechanical interface tolerances of the mounts. The RMS surface error at the mirror front surface is calculated to verify the wave front error budget requirements. The stresses due to bulk cool down, shock loads during launch are analyzed to compare against the margins of safety for yield and ultimate strength. The SWFFA finite element model (FEM) (Fig. 11) uses many different types of elements of which fifty thousand are tetrahedral.

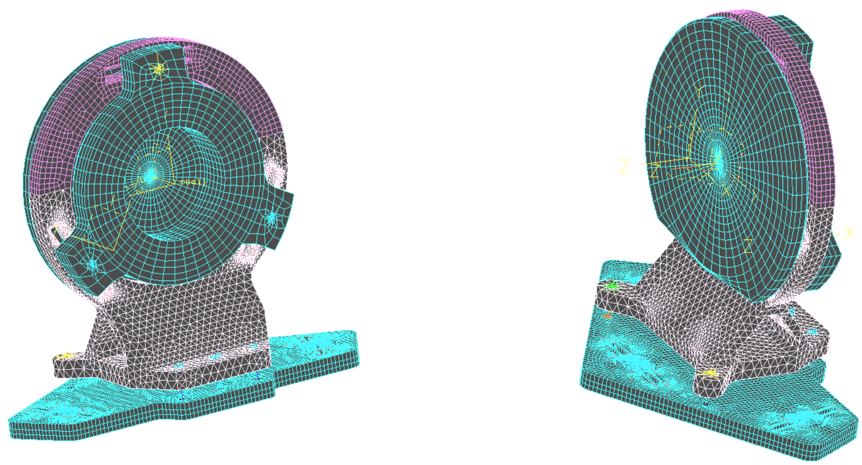

Figure 11. SWFFA Finite Element Model

The SWFFA has a first mode frequency (in Table 3 and Fig. 12) of 164 Hz, which meets the minimum 150Hz requirement.

Table 3. Modal Analysis Summary

Mode	Frequency (Hz)	Description
1	164	Mirror Pitch
2	295	Mirror Rock
3	506	Mount and Base Plate Bend
4	882	Mount Twist
5	890	Base Plate and Mount Base plate and mount
6	1156	Mount twist

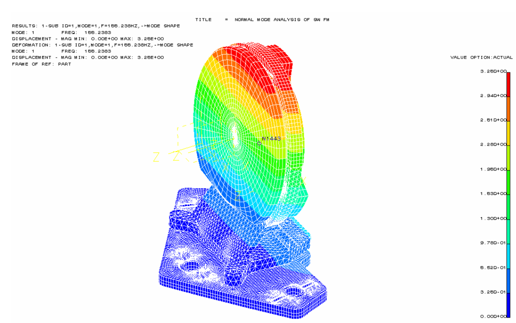

Figure 12. SWFFMA Mode 1 (164 Hz)
Full Scale is 0.0 to 3.25 nm.

The SWFFA shows nearly athermal behavior as well as minimal distortion due to 1G and mechanical preload. The distortion values (Table 4) are all well below the allocations.

Table 4. Surface Distortion Summary

Source	Predicted Error (nm RMS)	Allocation (nm RMS)
Cool Down (see Fig. 13)	2.9	10
1G sag Max	1.5	10
Mechanical Preload (67N at each)	4.4	5

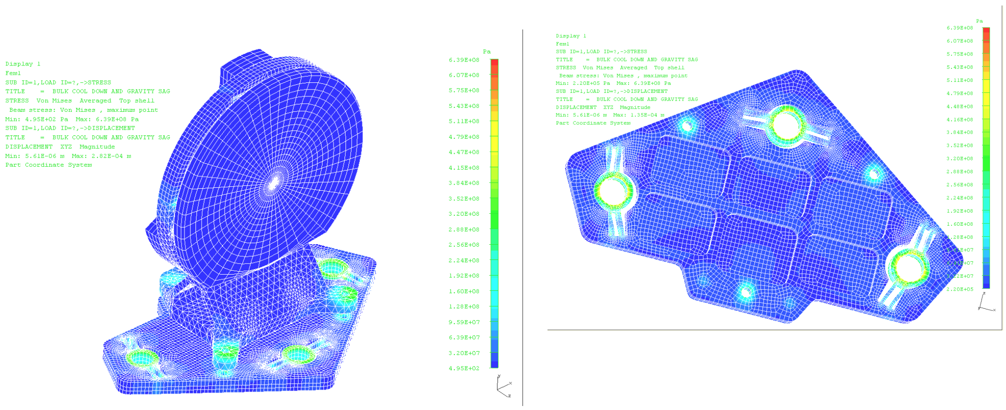

Figure 13. Bulk Cool Down Thermal Stresses peak at 40 to 50 MPa at the mounting holes

4. FOCAL PLANE ARRAY FOLD MIRROR ASSEMBLIES DESIGN

The FPA flat fold (FPAFF) mirror subassembly is a mounted, flat mirror (Fig. 14) that directs light toward the FPA. It is contained within the FPA housing to facilitate focal plane detector single chip array (SCA) radiation shielding. Each module contains one shortwave and one longwave FPA Flat Subassembly.

The FPA flat is rectangular shaped and lightweighted from the backside, with a triangular grid pattern. In three places, tabs protrude out of the rectangle. The tabs are in plane with the back surface of the mirror, but extend only half way towards the front surface. A pair of cantilevered spring clips load against each tab, contacting the mirror with PCTFE to reduce contact stresses. PCTFE pads on the back surface of the mirror oppose the load. The fixed ends of the springs are bolted to a titanium mount that frames the outside geometry of the mirror. The mount geometry properly “clocks” the mirror and shims secure the mirror for launch loads. As an added benefit, as the thermal environment changes from room temperature to 35 K the shims shrink proportionally to the titanium. The effect is two fold: 1) the mirror remains positioned correctly relative to the mount 2) only a very small amount of new “cool down distortion” is added to the mirror surface due to the significant change in temperature. The mount is nearly athermal.

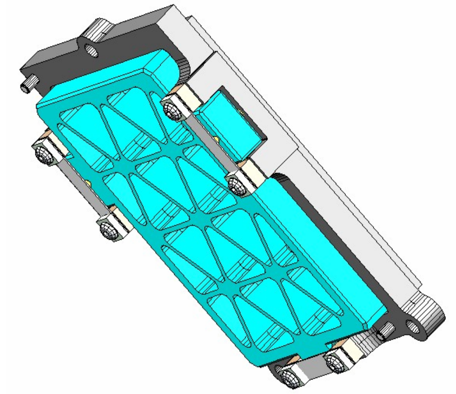

Figure 14. FPA Fold Mirror

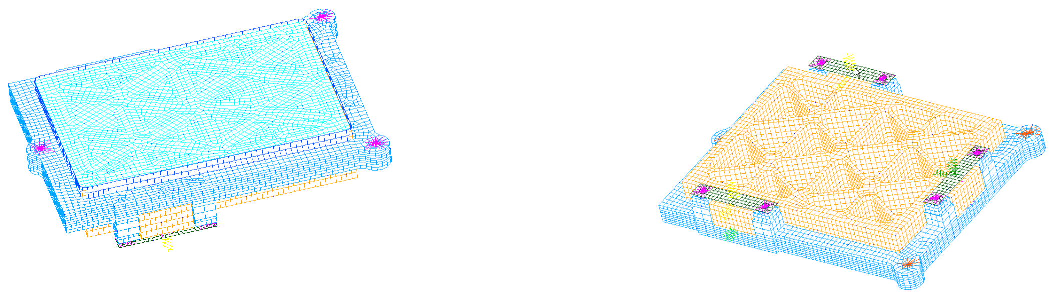

Figure 15. FPAFF Finite Element Model

4.1 FPAFF assembly analysis

The FPAFF assemblies are modeled using nearly thirty thousand grid points (Fig. 15). Similarly to the SWFFA modal analysis, the FPAFF has a first mode frequency (in shear) of 157 Hz (Table 5).

Table 5. Modal Analysis

Mode	Frequency (Hz)	Description
1	157	Shear
2	162	Shear
3	177	Despace
4	189	Tip/Tilt
5	295	Tip/Tilt
6	341	Tip/Tilt

The FPAFFA shows nearly athermal behavior as well as minimal distortion due to 1G and mechanical preload. The distortion values (Table 6) are all well below the allocations.

Table 6. Surface Distortion Summary

Case	RMS Calculated in nM	RMS Allowed nM
Gravity X	2.9	5
Gravity Y	2.8	5
Gravity Z	0.85	3
Bulk Cool Down	1.9	10
Temperature Gradient at operation	Negligible	4
Preload on retaining springs	4.4	7

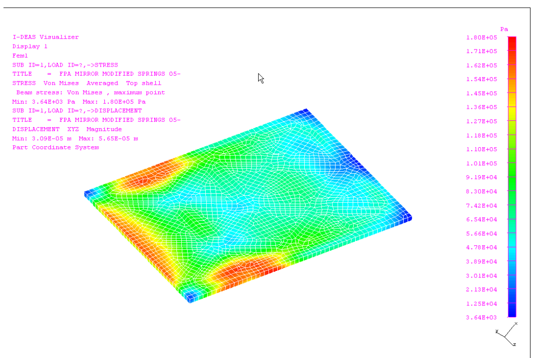

Figure 16. 54G Shock stress on mirror is 0.18 MPA maximum

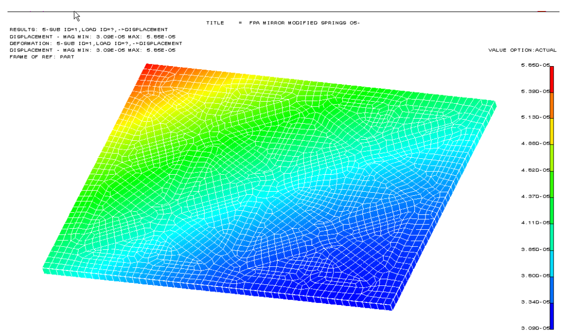

Figure 17. Bulk cool down surface displacement is less than 300 nm corner to corner

5. LESSONS LEARNED

An early design of the POMA included bipod flexures that were bonded to the mirror's back hub. High stresses were predicted at the bonded interface after cool down due to drastically different dL/Ls. These predicted stresses led to significant mirror surface deformation predictions. A different iteration used ball bearings in vee grooves to account for small motions during cool down. For small motions, ball bearings tend to have hysteresis and as a result this configuration was shown to be unpredictable by analysis. Finally, clamped flexures were chosen and through analysis they were shown to be repeatable causing minimal surface distortion.

In analysis, small changes to the FEM mesh, boundary conditions, loads, and material properties sometimes have a large effect on the outcome. In this case, the sensitivity of the friction factor between PCTFE and fused silica has a significant impact on the results. Knowledge of these friction factors can be difficult to obtain, but the friction factors should be measured.

6. SUMMARY

All of the mirrors and/or mounts presented in this paper use geometric features, flexures, materials, and careful consideration of preloading and mount points in order to perform at or better than the required level after severe launch loading and then a dramatic cool down from room temperature to 35K.

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