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Thin substrate grating array for sounding rocket and satellite payloads

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ABSTRACT

This paper presents critical engineering aspects of a grating array for a sub-orbital rocket payload to make spectral observations in the soft X-ray regime. The off-plane grating mount is a natural solution to maximize throughput and resolution in the ¼ keV to 1 keV range while minimizing envelope and mass. Replicated radial groove gratings are matched to the convergence angle of the telescope beam to limit aberrations. These lightweight gratings are mounted and aligned in an array which is not only efficient for rocket payloads, but can also be made suitable for the X-ray Grating Spectrometer on Constellation X.

Keywords: array, Constellation X, diffraction, grating, grazing, off-plane, rocket, spectrograph, thermal, x-ray

1. INTRODUCTION

The University of Colorado has used off-plane grating mounts in sounding rocket applications with consistent success for many years. Rockets have limited envelope and mass restrictions that facilitate ongoing advances in off-plane designs with each consecutive mission. We have the potential to use the knowledge gained through this process to support or even improve instrument performance in satellite missions such as Constellation X.

Several publications exist describing how an off-plane mount differs from the traditional in-plane solution.[1,2] In general, off-plane gratings intersect the telescope beam at grazing incidence with the groove direction nearly parallel to the light path. The groove profile can be made radial to match the convergence angle of the telescope beam to limit aberrations. The light is diffracted onto the focal plane with separate orders falling in the shape of an arc. High energy throughput tends to be more efficient than in-plane configurations due to the low reflection angle and efficient groove illumination. Vignetting is easy to minimize or completely omit since the reflected arc of diffraction follows an expanding cone along the graze angle, rather than diffracting orders into an adjacent grating. However, its potential for high resolution is one of the off-plane mount's greatest advantages. Resolution can be optimized by using optical designs with high β values that spread out diffracted orders and employing sub-aperturing techniques, as described by Cash (1987, 1991).[1,3]

In the following sections we will discuss the opto-mechanical nature of an off-plane grating array designed for a sounding rocket payload. The majority of these ideas can be extrapolated to apply to satellite applications with more strict environmental requirements.

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1.1 Grating array in off-plane geometry

Envelope restrictions and the optical design lead us to an array of thin substrate gratings mounted in an off-plane configuration that maximizes resolution in a minimum space. The array shown in figure 1 is designed to work at a 2.5º graze angle, allowing gratings to be positioned only 6mm apart with no vignetting of the reflected beam. The replicated optical surface of each grating is 100mm x 110mm, and the substrate thickness varies from 4mm in the center to 2mm at either end along the z-axis.

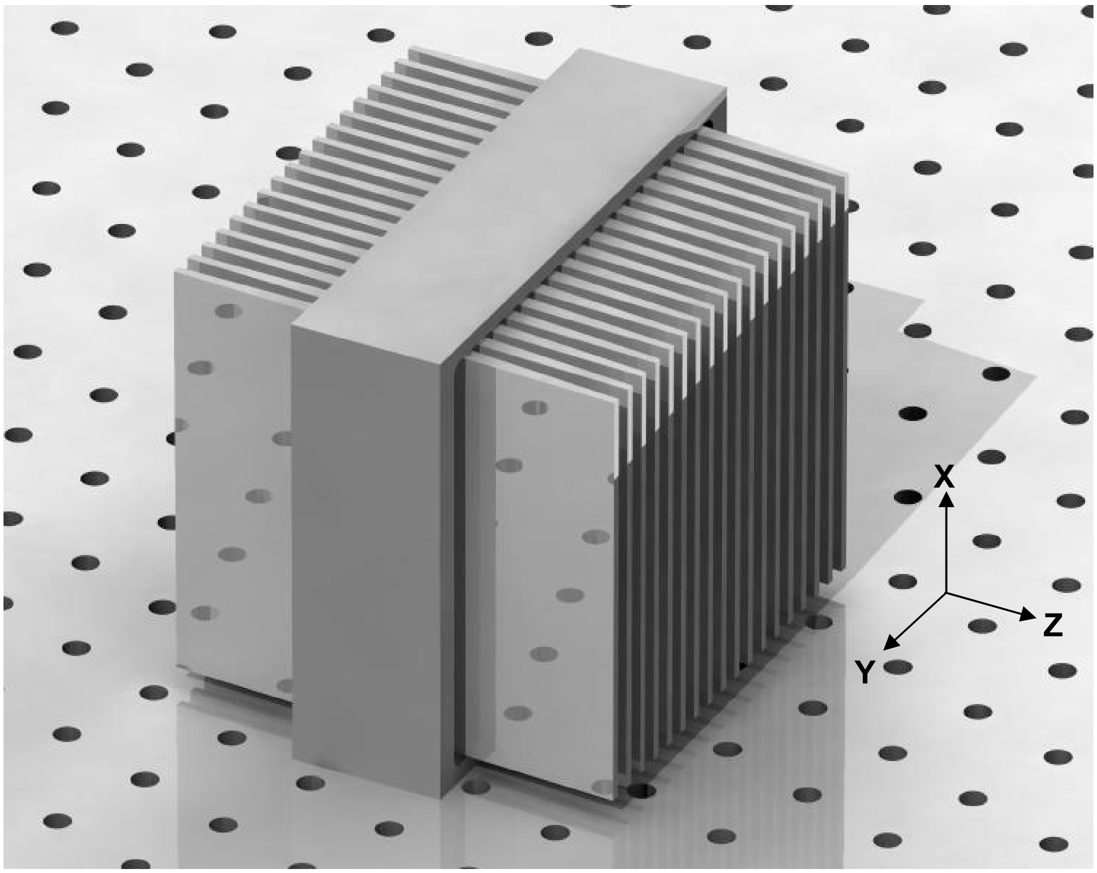

Figure 1. An array of off-plane gratings mounted in a holding fixture.

1.2 Off-plane grating tolerances

Table 1 shows allowable surface quality and orientation for gratings in our sounding rocket design with a desired specral resolution of 300.[4] The table is divided into four parts. The upper section defines optical surface flatness requirements in two directions. Pitch runs along the diffraction grooves or z-axis direction approximately parallel with the incoming beam. Roll is perpendicular to the grooves (x-axis). The lower section of the table quantifies the optical surface position in six degrees of freedom. Tolerances on the left side limit the zero-order image to a suitable size for dispersion, and on the right we show tolerances necessary to sustain the dispersed spectrum.

Analysis discussions in the following sections will focus on a design that meets pitch direction tolerances, since they tend to be tighter.

Table 1. Off-plane grating surface quality and position tolerances

Error Type	***Zero-order Allowable Tolerances***		***Spectrum Allowable Tolerances***	
	Equation	**Grating Res = 300**	Equation	**Grating Res = 300**
Pitch Slope error	$\zeta < \frac{\omega}{2}$	10 arcsec	$\zeta < \frac{ds}{F\sin\psi}$ *and* $\zeta < \frac{s}{F}$	20 arcsec
Pitch Surface error	$\delta < \frac{\omega h}{8n}$	1.2µm	$\delta < \frac{dsw}{4nF\sin\psi}$ *and* $\delta < \frac{sw}{4nF}$	2.8 µm
Roll Slope error	$\zeta < \frac{\omega}{2\sin\theta}$	229 arcsec	$\zeta < \frac{s}{2F\sin\theta}$	236 arcsec
Roll Surface error	$\delta < \frac{\omega w}{8n\sin\theta}$	30.5µm	$\delta < \frac{sw}{8nF\sin\theta}$	31.5µm
δ_x	$\delta_x < w$	(up to 11cm) Set at 1mm	$\delta_x < \frac{F\sin\theta}{R\sin\psi}$	150µm
δ_y	$\delta_y < \frac{\omega F}{2\cos\theta}$	121µm	$\delta_y < \frac{ds}{\sin\psi}$ *and* $\delta_y < s$	250µm
δ_z	$\delta_z < h$	(up to 10cm) Set at 1mm	$\delta_z < \frac{F}{R}$	8.3 mm
ϕ_x (pitch)	$\phi_x < \frac{\omega}{2}$	10 arcsec	$\phi_x < \frac{ds}{F\sin\psi}$ *and* $\phi_x < \frac{s}{F}$	20 arcsec
ϕ_y (yaw)	$\phi_y < \frac{2w}{h}$	126 deg	$\phi_y < \frac{\sin\theta}{R\sin\psi}$	30 arcsec
ϕ_z (roll)	$\phi_z < \frac{\omega}{2\sin\theta}$	229 arcsec	$\phi_z < \frac{s}{2F\sin\theta}$	236 arcsec

Where δ =allowable linear error, ϕ =allowable angular error, ω = telescope resolution, θ = graze angle, n=# of waves in surface error, w = grating width, h=grating height, and F=distance from gratings to detector, R=resolution ($\lambda/d\lambda$), s=telescope spot size, ds=sub-apertured image width, ψ=azimuthal position of grating on telescope.

Quantified tolerances: ω=20arcsec, θ = 2.5°, w=11cm, h=10cm, n=1, F=2.5m, s=250µm, ds=0, ψ=0°

2. OPTO-MECHANICAL ANALYSIS

Each grating substrate is trapezoidal in shape and flexure mounted at opposing ends.[5] Substrates designed for a sub-orbital rocket application consist of 7075-T6 aluminum, but may also be made from beryllium, silicon carbide or another material for satellite applications. High density diffractive grooves are replicated onto a polished substrate surface, and are located quasi-parallel to an incoming telescope beam. See figure 2. In this section we show the results of finite element analyses (FEA) to evaluate the effect of environmental conditions on an aluminum grating substrate.

2.1 Fundamental frequency and quasi-static load

Fundamental frequency of a substrate fixed at the ends of each flexure is estimated at 415 Hz. This frequency can be used to estimate an equivalent quasi-static load due to the dynamic environment under launch.[6] Power spectral density at this frequency with some amplification using Terrier Black Brant IX random vibration levels produce about 22grms quasi-static load. We use a customary 3σ design load at 65g, resulting in predicted maximum stress of 5400psi at the base of each flexure. Estimated displacement of a substrate at this 3σ load is less than 10 microns, so there is more than adequate space between gratings to avoid collision during vibration at launch.

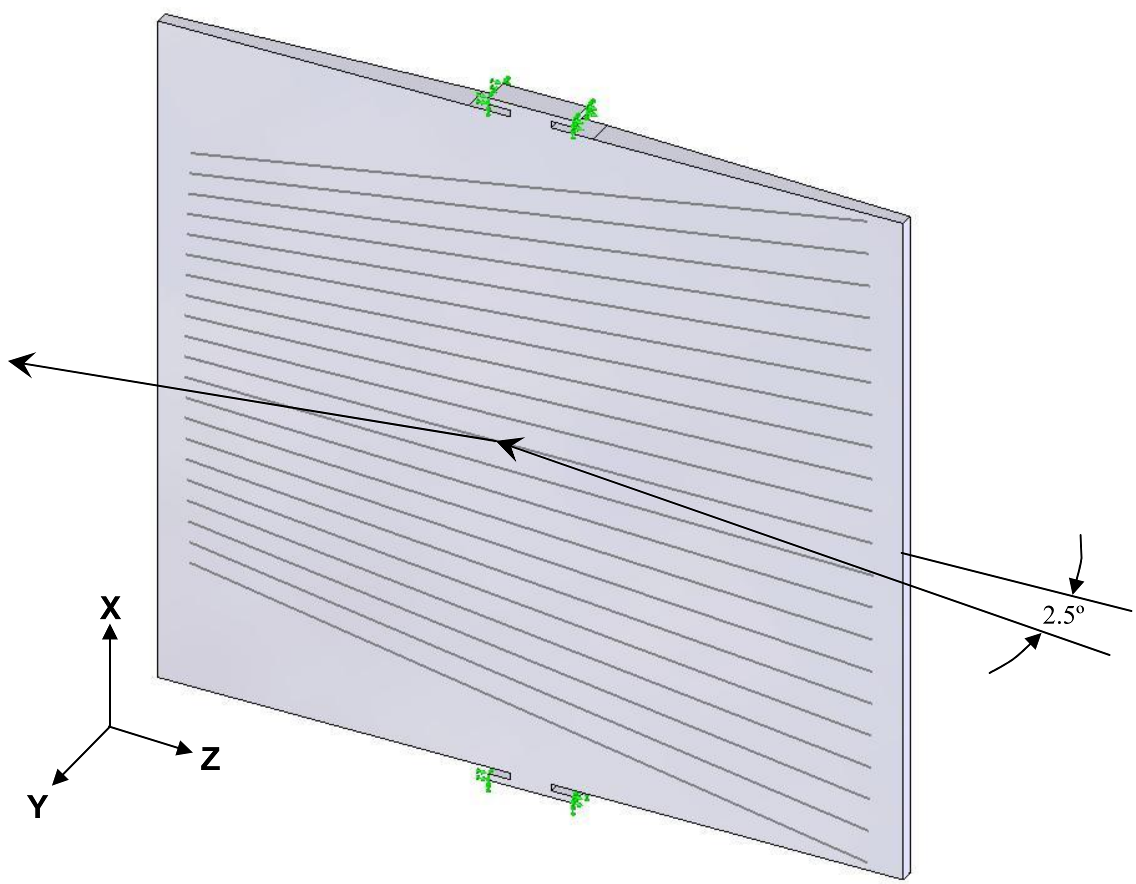

Figure 2. Grating substrate fixed at flexure ends. Incoming beam from right at grazing incidence.

2.2 Gravitational displacement

Gravitational displacement of a grating held at the extents of each flexure is greatest in the direction perpendicular to the optical surface (along the y-axis). This displacement is about one micron between the grating center and either end along the z-axis or groove direction as shown in figure 3. During assembly and alignment into an array, gratings will be held in a vertical position with 1g along the X axis. Maximum displacement in this orientation is predicted at only 13nm and well within allowable tolerances.

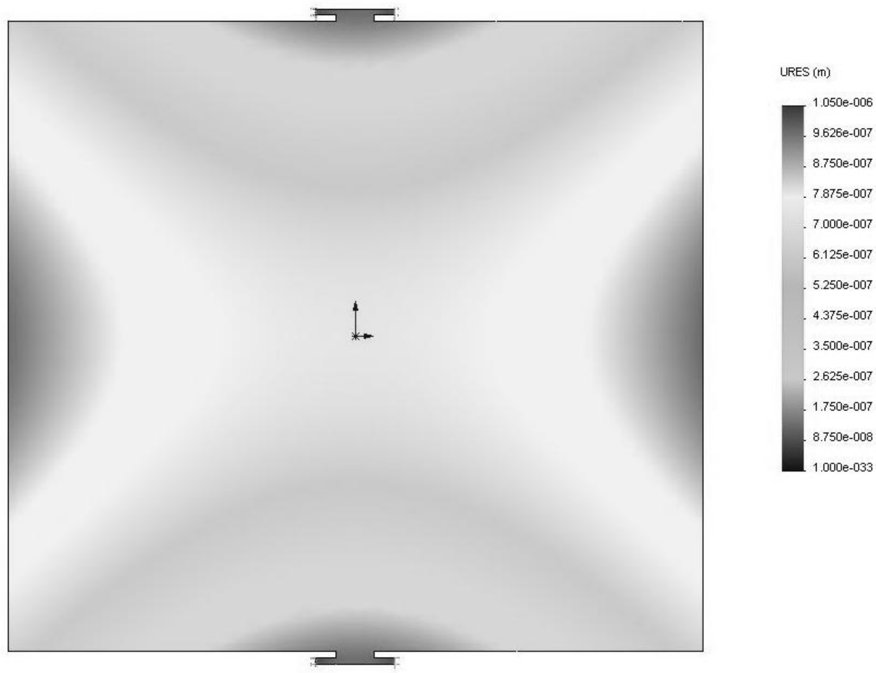

Figure 3. Grating substrate maximum 1g displacement (into page)

2.3 Thermal gradient

Optical surface errors can also be introduced by a thermal gradient across the grating substrate. Figure 4 shows expected surface displacement when the substrate's left edge is held at room temperature and its right edge is raised 1ºC. The result is a circular depression slightly left of center with raised corners on the right side. The maximum peak to valley difference is about 1.5 microns for an aluminum substrate fixed at its flexure mount points. Note that this analysis represents the effect of thermal gradient on a grating substrate independent of its mount. Maximum stress for this case is exhibited in the fixed flexures shown in Figure 4. This surface error may be considerably reduced with a clever athermal mount design that reduces flexure stress.

For instance, our proposed sounding rocket design employs an aluminum mount with a thermal coefficient matched with the grating substrates. Such a design will allow the flexure mount points to move unimpeded with the mount, thereby reducing stress and surface error. Similar methods may also be used to reduce thermal effects on substrates made of silicon carbide or beryllium, although gradients often remain a significant driver in satellite designs. Careful consideration given to optical mounting techniques can greatly ease environmental requirements.

Another technique for optimizing surface accuracy is to oversize the substrate enough to eliminate areas that contribute the most error. This method is commonly used in lens mounts, where the central portion of a lens meets specifications and the area near its perimeter is neglected. A comparison of figures 6 and 7 illustrates this concept. The plot in figure 6 represents a probe of ten points from left to right along the z-axis (pitch direction) through the grating center. Surface displacement across the first 40% of the grating remains relatively flat, and then rises steadily as it approaches the right side. The probe points in figure 7 run along the top edge of the grating, just below the flexure. Here we see a zone that contributes largely to the overall surface error. Increasing the width of the grating between the flexures so that the top and bottom edges are removed from active area will improve surface accuracy about 20%. Therefore, a 1ºC gradient would be allowable across each aluminum grating in our sounding rocket design. Given the high thermal conductivity of the aluminum substrate and short flight time of sub-orbital rockets, gradients do not impose a driving contribution in this tolerance budget.

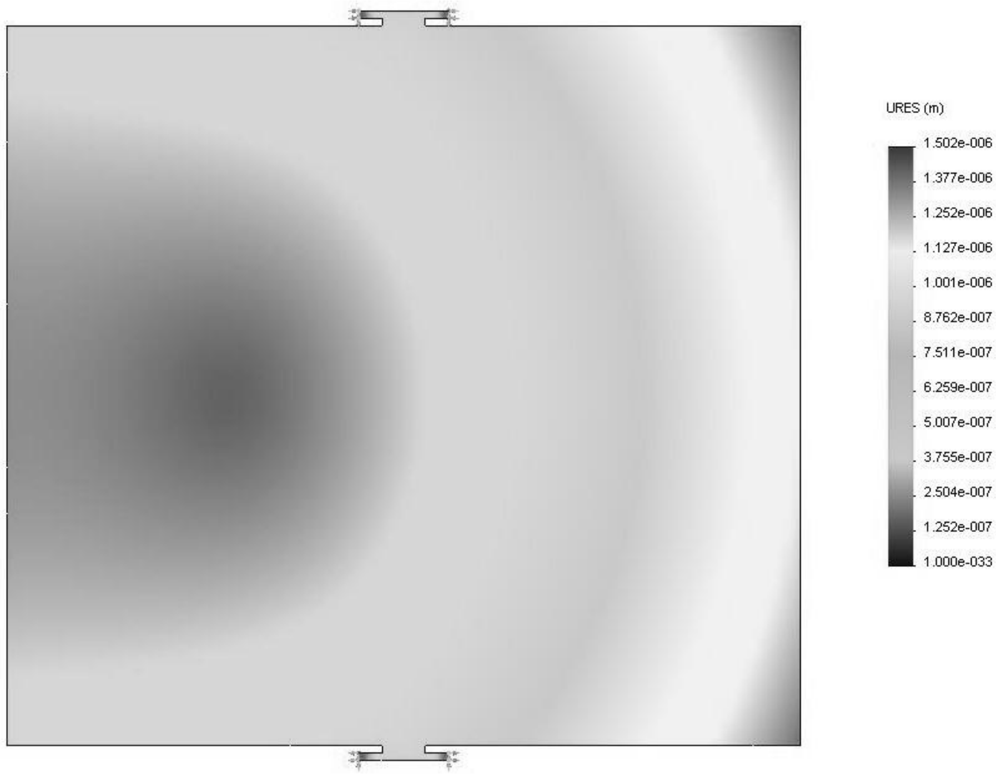

Figure 4. Optical surface displacement due to +1ºC gradient, left to right side

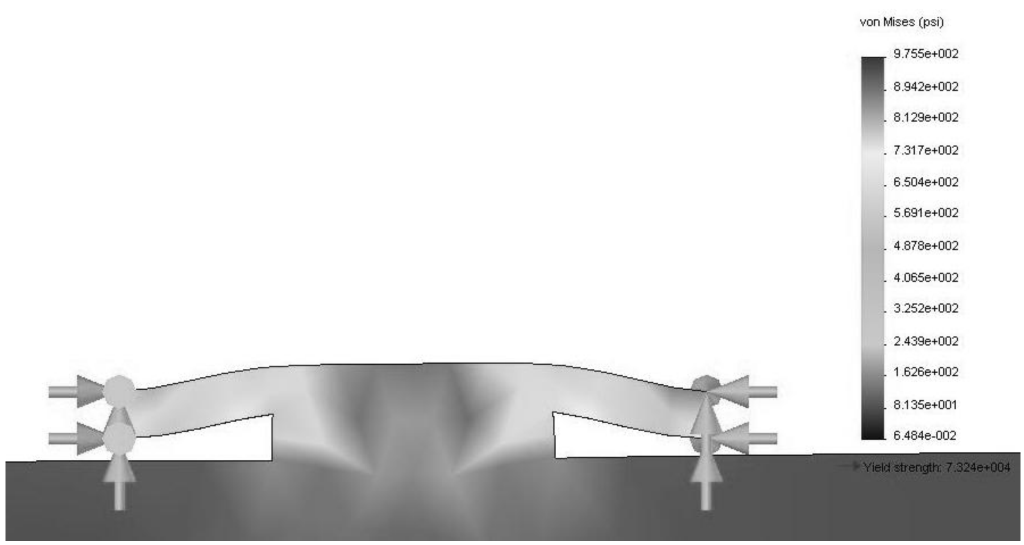

Figure 5. Stress in grating flexure due to +1C thermal gradient

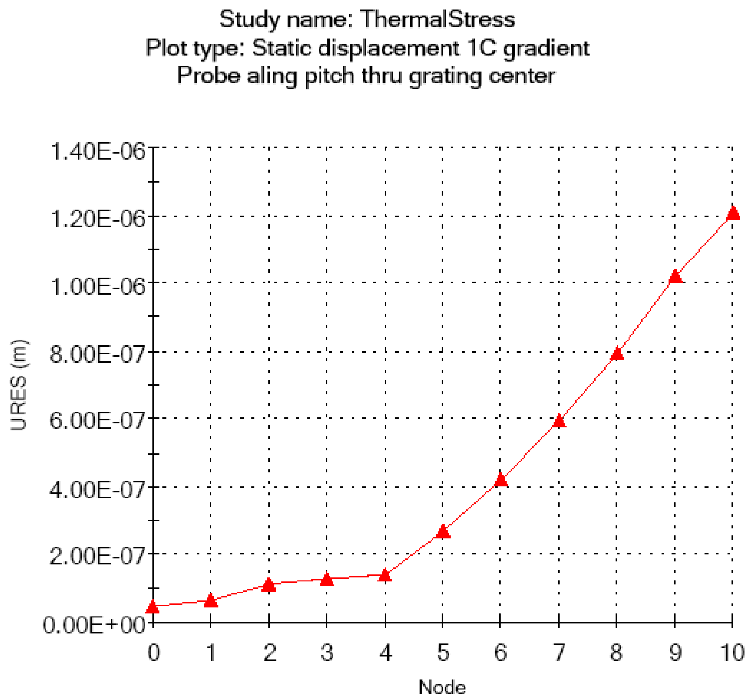

Figure 6. Optical surface displacement along grating central grooves due to 1C temperature gradient

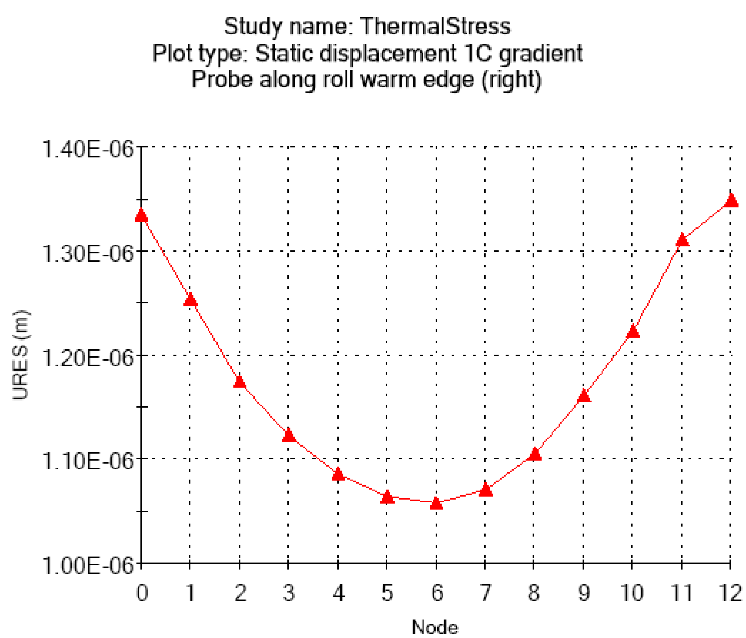

Figure 7. Optical surface displacement along grating edge due to 1C temperature gradient

2.4 Bulk temperature change

A uniform 1ºC temperature increase of a grating held at the extents of each flexure imposes both stress and surface errors. Lighter shades in the central vertical section of the plot in figure 8 show where the trapezoidal substrate is 4mm thick. Stress is fairly uniform at about 200psi in this section, extending through most of the flexure bodies above and below. Right and left edges taper to a 2mm thickness and carry about 100psi. Stress is concentrated and highest at the flexure attach points (not visible in this plot). The darker sections in the central areas are where stress is lowest. As described in section 2.3 above, this analysis represents the effects on a grating substrate independent of its mount.

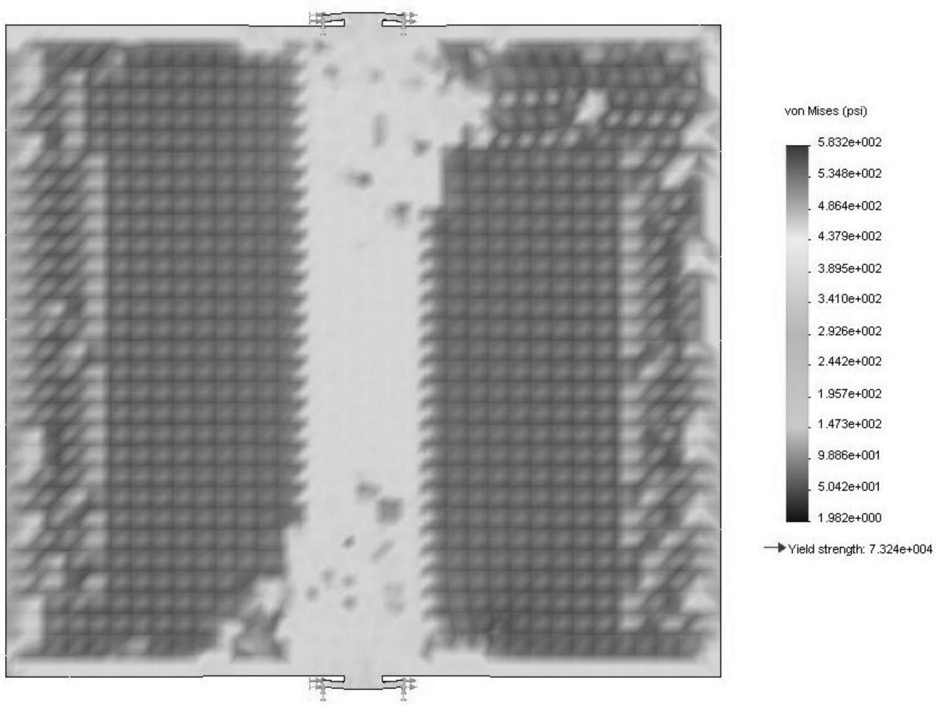

Figure 8. Optical surface stress due to +1C bulk temperature change. Highest stress is at mounting edge of flexures, lowest stress is dark areas in central areas.

Optical surface displacement shown in figure 9 also loosely indicates where the substrate is thickest and it's attach points are located. Once again, we observe a circular depression extending outward into a bowl shape with the furthest extents (corners) revealing the largest change from nominal position. This time, there is more stability in the roll direction along the x-axis between the flexures, where tolerances are looser. A probe in the pitch direction through the central part of the substrate (see figure 10) indicates an allowable temperature range of more than ±4ºC with the attach points fixed in a noncompliant mount. A thermally matched mount will notably improve performance. Again, we can see that oversizing the substrate will eliminate the largest displacements.

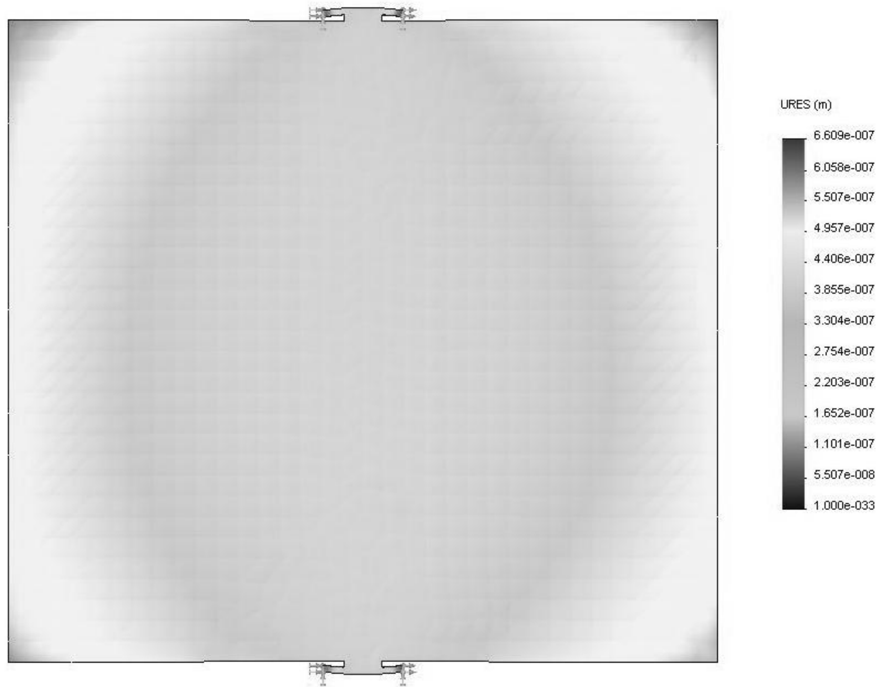

Figure 9. Optical surface displacement due to +1C bulk temperature change

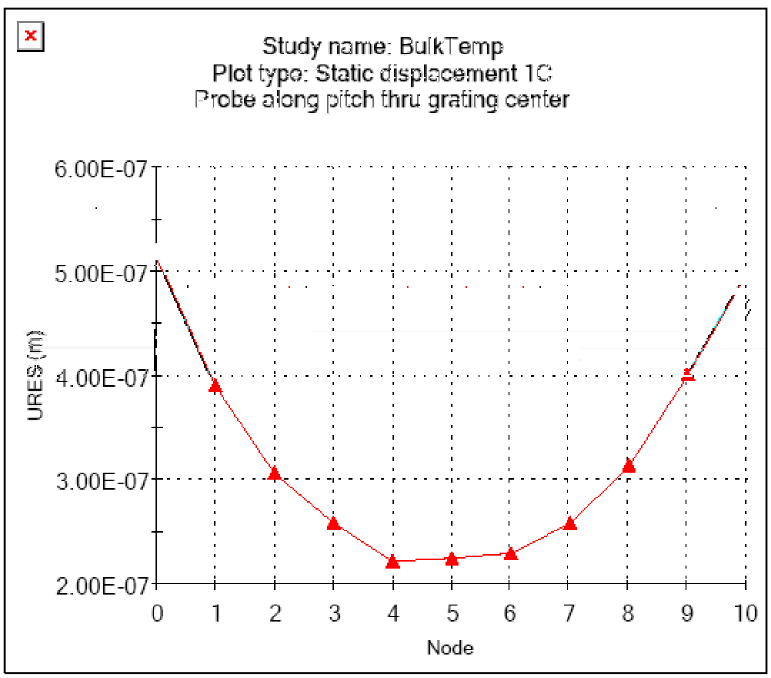

Figure 10. Optical surface displacement along grating central grooves due to +1C temperature change

3. CONCLUSION

Careful attention to opto-mechanical engineering can significantly improve the already recognized advantages of off-plane grating mount performance. Although we have evaluated parameters for a rocket payload spectrograph in this paper, designs are available that support vastly higher resolution. Employing a cleverly made off-plane grating mount has the potential to increase scientific return for missions like Constellation-X.

ACKNOWLEDGEMENTS

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