Synopsis: Effects of Temperature Changes in Opto-Mechanical Systems
Chapter 14 of "Mounting Optics in Optical Instruments" by Paul R. Yoder, Jr.

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Introduction

The effects of temperature changes on opto-mechanical systems are important to understand in order to design stable systems. Opto-mechanical systems in defense and aerospace industry are often subjected to extreme temperature changes in a short period of time. During these temperature changes, optics may experience changes in surface radii, surface figure, air space, thickness, indices of refraction, and thermal gradients. The physical dimensions of the structure holding the optics also change and in turn change contact stress and preloads. All of these changes within the opto-mechanical system cause defocus and misalignment errors. Techniques to prevent these changes with temperature include passive and active athermalization.

Athermalization Techniques for Reflective Systems

Athermalization is the process of stabilizing the optical performance of a system by choosing a configuration of materials and dimensions to compensate for the effects of temperature changes. For reflective systems, one method of athermalization is to make the entire system out of the same material. The Infrared Astronomical Satellite cassegrain telescope was built with beryllium optical and mechanical components. All components have the same CTE and thus change by the same amount.

If the optics and mechanical structures are of differing materials, one method to correct focus errors is by active control of the mirrors. Focus sensing components could be added to optimize performance but this adds cost and complexity. Mirrors are usually made of near zero CTE materials such as ULE or Zerodur. The other option for athermalization of systems with differing CTEs is by passive athermalization. This is accomplished by using "metering rods" between primary and secondary mirror structures. The passively compensated structure of the Geostationary Operational Environmental Satellite is schematically depicted in Fig. 1.

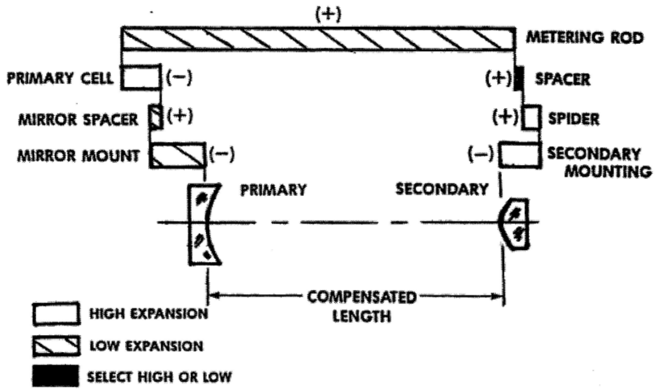

Fig. 1 Passively compensated structure of the GOES Telescope

The air space between the mirrors remain constant when the temperature ranges from 1°C to 54°C by using materials of high and low CTE within the truss and mounting. In order to have zero air space change, the lengths of the metering rods must be longer than the optical system. Instead of using different materials within the truss system, each member of the truss may be made of a near zero CTE material such as graphite fiber reinforced epoxy. The Hubble Space Telescope secondary support system was constructed in this way.

Athermalization Techniques for Refractive Systems

With refractive and catadioptric systems, the designer must now take into account refractive index variations. The refractive index of air at $15°C$ is

$$(n_{AIR\ 15})x10^8 = 6432.8 + \left[\frac{2949.810}{146-\left(\frac{1}{\lambda}\right)^2}\right] + \left[\frac{25540}{41-\left(\frac{1}{\lambda}\right)^2}\right]$$

and the index variation of air with temperature is

$$\frac{dn_{AIR\ 15}}{dT} = \frac{(-0.003861)(n_{AIR\ 15}-1)}{(1+0.00366\ T)^2}$$

The change in focal length Δf of a single element thin lens for a change in temperature ΔT can be defined as

$$\Delta f = -\delta_G f \Delta T$$

where δ_G is a glass coefficient of thermal defocus and is equal to

$$\delta_G = \left[\frac{dn_G/dT}{(n_G)(n_{AIR\ 15})-1}\right] - \alpha_G$$

The term dn_G/dT can be obtained from glass catalogs and α_G is the glass CTE and is positive for all refracting materials.

Passive athermalization of refracting systems is accomplished by designing mounts from multiple materials to make the changes in dimensions of the mount equal to the change in BFL for the same ΔT. Fig.2 shows two types athermal mountings for refractive systems.

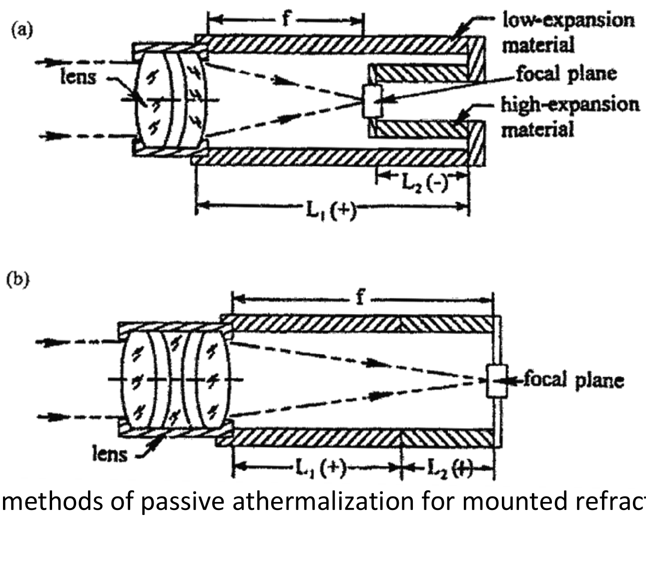

Fig.2 Two methods of passive athermalization for mounted refractive systems

The design equations for passive athermalization using two mounting materials of CTE α_1 and α_2 and lengths L_1 and L_2 are

$$\delta_G f = \alpha_1 L_1 + \alpha_2 L_2$$

where

$$L_1 = f - L_2 \qquad \text{and} \qquad L_2 = f\frac{(\alpha_1 - \delta_G)}{(\alpha_1 - \alpha_2)}$$

Optical design software may be used for thermal modeling and creating athermal mounts.

Active compensation of refractive systems involves adding axial motion control for one or more optical elements. Probes must be used to continually monitor temperature changes within the optics and changes are made to the optics to achieve optimum performance based on a pre-established algorithm.

Effects of Temperature Changes on Axial Preload

Change in axial preload with temperature change is caused by the dissimilar CTEs of the optics and mounting hardware. The relationship can be quantified by

$$\Delta P = K_3 \Delta T$$

where K_3 is the rate of change of preload with temperature and is normally negative.

For most optical systems, the CTE of the mount exceeds the CTE of the optics. For an increase in temperature, the mount will expand more than the optic and axial preload P_A at assembly temperature T_A will decrease. The axial preload goes to zero at temperature

$$T_C = T_A - \left(\frac{P_A}{K_3}\right)$$

For temperatures above T_C, the lens is no longer in contant with the mount and the increase in this gap is approximated as

$$\Delta_{\mathrm{GAP\ A}} = \sum_{\mathrm{i=1}}^{\mathrm{n}} (\alpha_M - \alpha_i)(t_i)(T - T_C)$$

Where n is the number of optical elements +spacers and t is element/spacer thickness. If T_C is larger than the maximum temperature experienced by the system, $\Delta_{\mathrm{GAP\ A}}$ is negative and no gap is formed. If the opto-mechanical system experiences large accelerations at high temperatures, it is advisable to design the lens assembly to have sufficient preload at this extreme to avoid fretting.

The term K_3 (rate of change of preload with temperature) may be approximated by considering only bulk effects. It is quantified as

$$K_{3\,BULK} = \frac{-\sum_{i=1}^{n}(\alpha_M - \alpha_i)t_i}{\sum_{i=1}^{n} C_i}$$

Where C_i is the compliance of one of the elastic componenets in the subassembly (lens, cell, spacer).

One technique for reducing the rate of change of preload with temperature is to make the design axially athermal so dimensional changes are passively compensated. This is accomplished by using metals with CTEs close to glass and by changing the dimensions of spacers by adding bevels into the lenses.

Radial Effects in Rim Contact Mountings

Radial clearances around lenses and spacers tend to increase with an increase in temperature and shrink when temperature decreases. Radial stress and hoop stress may occur at lower temperatures if clearances are small enough at assembly. The radial clearance provided at assembly will also increase with a rise in temperature and will in turn cause decenter or tilt if axial preload is insufficient to hold the lens in place. When temperature returns to assembly temperature, the lens may be constrained while decenterd and system performance may degrade.

Radial stress at reduced temperatures may be estimated as

$$S_R = -K_4 K_5 \Delta T$$

where

$$K_4 = \frac{(\alpha_M - \alpha_G)}{\left(\frac{1}{E_G}\right) + \left[\frac{D_G}{(2E_M t_C)}\right]} \qquad \text{and} \qquad K_5 = 1 + \left\{\frac{2\Delta r}{[D_G \Delta T(\alpha_M - \alpha_G)]}\right\}$$

D_G is the optic OD, t_C is the mount wall thickness outside the rim of the optic, and Δr is the radial clearance at assembly. Tangential or hoop stress in the mount wall may be found from

$$S_M = \frac{S_R\left(\frac{D_G}{2}\right)}{t_C}$$

This equation may be used to determine if the mount is strong enough to withstand the force exerted on the optic without exceeding its elastic limit.

Effects of Temperature Gradients

When different temperatures exist within an opto-mechanical system, a thermal gradient exists. These gradients may also be changing with time and can exist axially or radially. Thermal shock occurs when an optical system experiences rapid temperature changes.

A radial gradient is illustrated in Fig.3 where the glass near the rim is warmer than that near the axis.

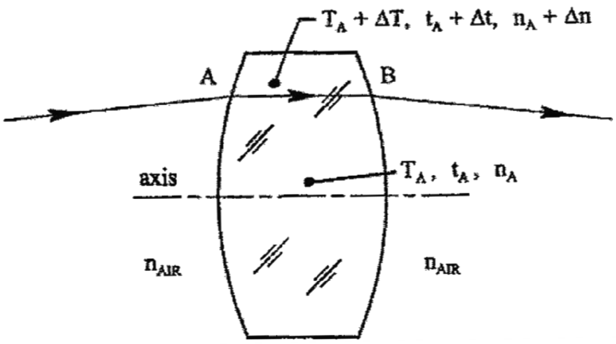

Fig. 3 Radial gradient in singlet

The OPD between the ray passing through A and B compared with a ray passing through the optical axis is approximated by

$$OPD = \left[(n_G - 1)(\alpha_G) + \frac{dn_G}{dT}\right] t_A \Delta T = (n_G - 1)(\gamma_G t_A \Delta T)$$

Where γ_G is the thermo-optical coefficient defined as

$$\gamma_G = \alpha_G + \left[\frac{dn_G/dT}{(n_G - 1)}\right]$$

Optical plastics and some infrared materials (germanium) have large γ_G and are thus sensitive to spatial temperature variations. Radial temperature gradients in mirrors will change radii and in turn optical figure.

Axial temperature gradients within optics may be created from absorption of incident heat flux. An optical window will bend under these conditions and the optical power is given by

$$P = \left[\frac{(n-1)}{n}\right]\left[t\frac{q}{k}\right]^2$$

where q is the heat flux per unit area and k is the thermal conductivity. For a mirror, the change in curvature when exposed to an axial gradient is given by

$$\left(\frac{1}{R_o}\right) - \left(\frac{1}{R}\right) = \left(\frac{\alpha}{k}\right) q$$

Where R_o is the original ROC and R is the new ROC.

Temperature Change-Induced Stresses in Bonded Optics

The three major sources of stress in bonded joints are shrinkage of the adhesive, acceleration that shears the joint, and differential expansion and contraction at high and low temperatures. Shrinkage of the adhesive tends to bend the optic. The optic usually fails before the adhesive when subjected to accelerations normal to the bond joint. A cemented doublet is a common example of bonding two materials with different CTEs. The equation for estimating shear stress in a thin bond between glass-to-glass or glass-to-metal is

$$S_S = \frac{2(\alpha_1 - \alpha_2)(\Delta T)(S_e)[I_1(x)]}{t_e \beta (C_1 + C_2)}$$

where

$$S_e = \frac{E_e}{(2)(1 + \nu_e)} \qquad \text{and} \qquad \beta = \left\{\left(\frac{S_e}{t_e}\right)\left[\frac{(1-\nu_1^2)}{E_1 t_1} + \frac{(1-\nu_2^2)}{E_2 t_2}\right]\right\}^{\frac{1}{2}}$$

$$C_1 = -\left[\frac{2}{(1+\nu_1)}\right]\left\{\left[\frac{(1-\nu_1)I_1(x)}{\beta R}\right] - I_o(x)\right\} \quad \text{and} \quad C_2 = -\left[\frac{2}{(1+\nu_2)}\right]\left\{\left[\frac{(1-\nu_2)I_1(x)}{\beta R}\right] - I_o(x)\right\}$$

Here, α_1 and α_2 are the CTEs of the two bonded parts, ΔT the change from assembly temperature, S_e is the shear modulus of the adhesive, R is one half the lateral dimension of the circular bond, t_e is the thickness of the adhesive layer, E and ν are Young's modulus and Poisson's ratio, $t_1$and t_2 are the thicknesses of the bonded parts, and $I_o(x)$ and $I_1(x)$ are modified Bessel functions of the first kind. The tensile stress tolerance for glass is 1000 lb/in.[2] and may be used to predict fracturing of cemented optics at extreme temperatures.

Conclusion

The stability of opto-mechanical systems under changing temperatures is very important to analyze during the design process and this synopsis gives a starting point for such studies. The key points in this synopsis may be extremely valuable to optical engineers in the aerospace industry and defense. Opto-mechanical systems in these fields are often required to operate flawlessly in radically changing temperature environments. Examples include remote sensing systems in Earth orbit and aerial surveillance cameras on high altitude manned flights. This synopsis also covers the basics of preventing failure of optics due to induced stress. Multi element refractive systems are extremely expensive and lens failure is not an option.