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AN ATHERMALIZATION LENS BARREL STRUCTURE FOR IR OPTICAL SYSTEM

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Abstract: We have developed an athermalization barrel containing 4 IR lenses. It consists of two materials with different coefficients of thermal expansion (Invar and aluminum). A finite element analysis and the experiment data showed that this new athermalization barrel has a defocus error sensitivity of 8.1 nm/°C, which satisfies our requirement for high resolution camera.

Keywords: IR, athermalization, barrel, Invar.

1. INTRODUCTION

Modern optical systems are expected to operate in a wide temperature range from –40 to +70 °C, although such changes in temperature can be deleterious to the maintenance of image quality, especially for high-performance optical systems. Optical systems operating in such wide temperature ranges tend to suffer from changes in the shape of their optical surfaces, in their thicknesses, in their refractive indices (i.e., the thermo-optic effect), and in the distance and tilt angle between their optical elements, all of which result in the degradation of their optical system performance.

Figure 1 shows a schematic diagram of a mid-IR reimaging optical system with a focal ratio of f/2.7 as an example of a high-performance optical system designed to operate over a wide temperature range, which functioned as the target optical system for the athermalization technique studied in this work. The front-end four-mirror telescope delivers the incident light beam onto a dichroic beam splitter, M5, where it is divided into the Electro-Optical (EO) and Infrared (IR) bands. The EO band is focused onto a CCD directly after being reflected from M5, while the IR band is transmitted through M5 and focused onto an IR detector via the reimaging optics consisting of three mirrors (M6, M7, and M8) and four lenses (L1, L2, L3, and L4). We named this part of the system the "infrared optical assembly" (IROA). It was designed to meet the optical and mechanical requirements summarized in Table 1. The lens materials are silicon (Si) and germanium (Ge), and the mirrors are made of Zerodur. These were assembled with flexural supports and mounted onto a sandwich-paneled bezel that had an outer layer of carbon fiber reinforced plastic with a very low coefficient of thermal expansion (CTE) of -0.5×10^{-6} /°C and an inner layer composed of an aluminum (Al) honeycomb structure.

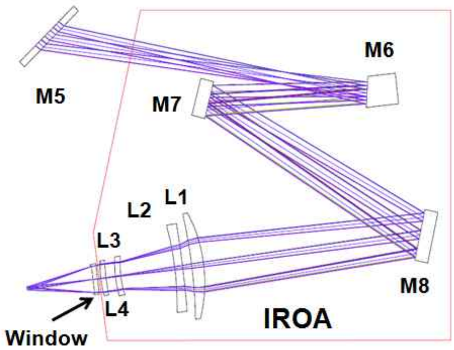

Fig. 1. A schematic diagram of the infrared optical assembly (IROA).

An initial thermal analysis revealed that the temperature gradient across the IROA in an operational environment was < 1 °C in the transverse and longitudinal directions, while the uniform temperature variation spanned 8 to 32 °C [1]. This means that the IROA would be exposed to a temperature variation of ±12 °C after being assembled at room temperature (20 °C). This can be regarded as a smaller temperature variation than that experienced in other application environments. However, the allowable degradation in the wavefront error (WFE) is stringent, considering the operational wavelength band. This poses a serious technical challenge to the athermalization of the IROA.

The IROA Zerodur mirrors (M6, M7, and M8) were mounted on the IR bezel using Invar flexural supports, and their lateral and axial displacements were expected to be negligible over the temperature range in this study. Therefore, any degradation in the performance of the IROA would be more sensitive to the thermoelastic lens distortion and the thermo-optic effect of the temperature-dependent refractive index of lenses. The simplest and conventional way of mounting the four lenses would have been to use a single cylindrical barrel, which is a precisely machined barrel accommodating the lenses at the designed locations. However, it is well known that this traditional barrel tends to suffer from poor athermalization performance, resulting in an unacceptable level of lens displacement that can cause a large defocus error and/or shift in focus.

We investigated a new three-shell-based barrel structure to provide a unique athermalization solution for a compact

IROA, and achieved a high negative distance shift between the lens and the focal plane in a compact way. In Section 2, the thermal characteristics of the IROA are analyzed using a simple single-shell barrel model. We explain the design of the new three-shell-based structure for effective athermalization and computational predictions of its enhanced optical performance in Section 3. Section 4 describes the experimental data for the superior thermoelastic performance of this new athermalization model compared with a single-shell barrel model and then concluding remarks are given in Section 5.

2. THERMOELASTIC ANALYSIS

As a baseline study of the thermoelastic effects from which our new three-shell-based barrel design evolved, we investigated the athermalization characteristics of a single-shell barrel structure designed to accommodate all the IROA lenses and detector module (i.e., the window, dewar, focal plane, and front-end electronics), shown in Fig. 2. The barrel was made of Ti6Al4V alloy for a close CTE match with the lens materials, i.e., either Ge or Si, and for its higher mechanical strength. The barrel dimensions were length = 270 mm and largest diameter = 159 mm. The back focal length (BFL) was about 100 mm. The lens barrel used three Invar flexural supports (i.e., two frontal and one rear support) to form a semi-kinematic support that was mounted on the bezel. Since the detector module is the heaviest component among all the IROA parts, weighing about 3 kg, the rear support was designed to be more rigid than the two front supports, so that the detector module was held tightly.

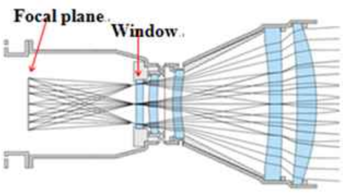

Fig. 2. The single-shell barrel model for an IROA

Mismatches in the thermo-optic material properties and the thermoelastic distortion of the lens are common causes of significant defocus errors for uniform temperature changes in IROA. First, we changed each lens's refractive index by dn/dT for a change of 1 °C and calculated the sensitivity to the defocus error expressed in terms of the defocus term in the Zernike circle polynomials [2]. The results show that while each lens had a significant degree of thermal sensitivity to the defocus error, the combined effect of these two factors turned out to be 9.7 nm/°C. This indicates that this IROA optical design achieved only a moderate degree of athermalization against thermo-optic effects.

Second, the thermoelastic distortion of each lens was analyzed using FE analysis. The numbers of elements and nodes were 102,591 and 188,784, respectively. The insert holes of each flexure were fixed onto the bezel, defining the boundary condition. The results of the FE analysis show that all the elements were shifted along the negative z-axis direction for a uniform temperature increase. This is caused by the relatively large CTE of titanium (approx. 9×10^{-6} m/m/°C) and by the rigid rear support. Lens L1 showed the largest –z-axis displacement of about 1.9 μm, while Lens L4 showed the least –z-axis displacement of 0.76 μm. The detector module (i.e., the window and focal plane) remained stationary.

The computed distortion of each lens surface was fitted to Zernike circle polynomials, and the first 36 coefficients were used to compute the variation in the IROA optical performance associated with the Zernike term coefficients (delta c). The combined thermoelastic effect turned out to be about 20.3 nm rms/°C, which exceeds the value defined from the IROA system requirements (15.0 nm rms/°C). The defocus error played a primary role, whereas the contribution from coma and/or astigmatism was negligible, implying that the lens barrel and/or flexure exerted an insignificant force on the lenses under temperature variation. The shift in focus could be calculated from the defocus error using Eq. (1) [8]:

$$\delta = -8 \times a_{20} \times \left(\frac{f}{\#}\right)^2 \qquad (1)$$

where δ is the shift in focus along the z-axis direction and a_{20} is the coefficient of defocus term r^2. For f/# = 2.7 and a_{20} = 50.0 nm (= $2[\sqrt{3}a_4 - 3\sqrt{5}a_{11} - 2\sqrt{6}(a_5^2 + a_6^2)^{1/2}]$ [3]), we obtained δ = –2.916 μm for a change in temperature of +1 °C, implying that a negative directional shift had occurred from the paraxial reference location. Therefore, to obtain an acceptable level of athermalization against any thermoelastic effects, our findings implied the need for a new and better barrel structure that was capable of producing a negative change in distance between the lens and focal plane as the uniform temperature rises across the IROA.

Considering that the BFL of the IROA was about 100 mm, the expected shift in the focal rate defined by Jamieson [9] was calculated to be about 29.16×10^{-6} m/m/°C, which is too large to be effectively compensated for by the original reentrant model discussed in Section 1. For example, if Invar36 (CTE ≈ 1×10^{-6} m/m/°C)and Al6061 (CTE ≈ 23×10^{-6} m/m/°C) were used for the thermal expansion combination of low- and high-expansion materials, then the length of the Invar36 and the Al6061 shells would have to be about 237 mm and 137 mm, respectively [4]. These long shell lengths are not practical and cannot satisfy the limited space constraint of our IROA. Further aggravating the situation is their insufficient structural rigidity against operational vibration.

3. THREE-SHELL-BASED LENS BARREL DESIGN

To achieve effective athermalization, we developed a new three-shell barrel model, as opposed to the original reentrant model consisting of two shells. Our design consists of three shell layers of the same length (100 mm), having a middle Al6061 shell with a large CTE sandwiched by two (i.e., outer and inner) Invar36 shells with a low CTE. The outer shell was designed to hold the lens, and the inner shell is fixed in the focal plane. In this way, the expansion of the middle shell can be fully exploited to generate the required negative change in distance between the lens and the focal plane.

Figure 3 shows the new athermalization LBS model. The front lens barrel is a solid hollow shell made of Ti6Al4V alloy that mounts all four lenses, which are bonded using an epoxy resin with a thickness of about 0.3 mm. The rear lens barrel is a cylindrical athermalization shell capable of producing a large negative change in distance between the lens and the focal plane. As can be seen in Fig. 3, the left-hand side of the outer shell is fixed to the rear lens barrel, and the right-hand side of the inner shell is attached to the front lens barrel. The Al6061 shell is sandwiched between these shells. The thickness of each shell is about 1.5 mm, and the diameter of the outer shell is 102 mm. The gap between the shells is maintained at 0.5 mm, and filled with an Al6061 spacer ring. Since the value of the CTE of Invar36 is much lower than that of Al6061, as the temperature changes, the thermal expansion of the barrel is dominated by the Al6061 middle shell.

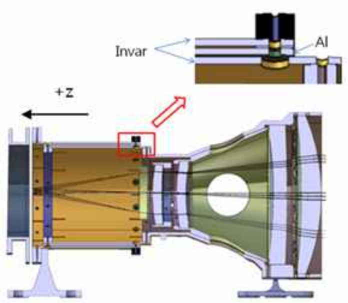

Fig. 3. A three-shell-based athermalization structure

The rear support has the highest rigidity among the three supports of the lens barrel, similar to the LBS shown in Fig. 3, while the shape of the front two supports was changed to be more flexible in the +z-axis direction. As the shell length was 100 mm, it was expected to produce a change in physical distance of about –2.2 μm/°C between the final lens surface and the end of the lens barrel. Although this did not fully compensate for the expected focal shift of the IROA of –2.916 μm/°C, the residual focal shift was only –0.716 μm/°C, which is only a quarter of the focal shift of the IROA. A different set of materials with a larger difference in their CTE values is required for full compensation of the total shift in the IROA focus.

The FE analysis of the modified LBS showed that the positive displacements of Lenses L1 and L2 dominate the thermoelastic distortion. The distortion of each surface was used to calculate the lens optical performance. The change in defocus error caused by the new athermalization model was reduced from 20.1 nm (i.e., the single LBS model) to 1.9 nm for a change of 1 °C in the uniform temperature. When combining the thermo-optic and thermoelastic effects, the thermal sensitivity to the defocus error for the new athermalization LBS was reduced to only 11.6 nm/°C from the value of 29.8 nm/°C for the single LBS model. The slight reduction in terms of astigmatism and trefoil comes from the more flexible front supports, even though this reduction is not critical in our development.

4. EXPERIMENTAL VERIFICATION

The LBS forms part of a larger optical system involving a common front-end telescope and mirrors M6–M8 that were not available at the time of the athermalization experiments. Therefore, the LBS wave-front test configuration used a computer generated hologram CGH designed and built in-house, as shown in Fig. 4. The CGH was designed to compensate for all aberrations from the optical design of the lenses. The IR interferometer produced a converging beam (λ = 3.39 μm) that was focused in the nominal focal plane, and it then passed through the LBS lenses. The beam followed the same path, returning to the interferometer after reflecting from the CGH. The CGH had a diameter of 50 mm, and the minimum pitch of the pattern was 20 μm.

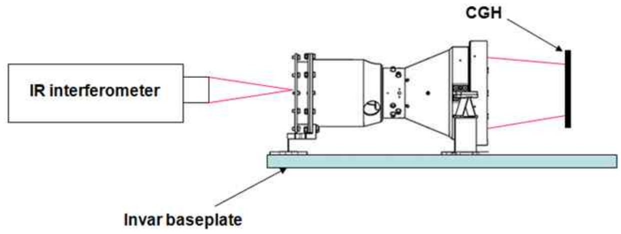

Fig. 4. Layout of the thermal sensitivity tests for the LBS.

The LBS was placed inside a thermal shroud, while the interferometer and CGH were located outside it, so that they would be free from any distortion or displacement caused by a change in temperature inside the shroud. Furthermore, the LBS was mounted on an Invar baseplate so that the relative displacement of the LBS with respect to the interferometer and the CGH would be minimized during any thermal changes.

Six Type K thermocouples with a self-adhesive backing (Model SA1 series) [5] and a 16-channel thermocouple reader (Model SR630) [6] were used to monitor the temperature distribution across the LBS. The resolution of the temperature reading using the Type K thermocouples was 0.1 °C, and the accuracy was 0.5 °C. The thermocouples were fixed at the six locations shown in Fig. 8. The lens surface temperature was not measured directly to avoid any potential damage and/or contamination of the coated optical surface. The thermal conductivity of the lens materials was 59 W/mK for Ge and 150–163 W/mK for Si; both of these values are much higher than the value of Ti6Al4V (6.6 W/mK) [7]. This ensured that the lens temperature stabilized faster than the Ti lens barrel. Furthermore, each WFE measurement was performed for periods longer than 1 h after the lens barrel temperature had stabilized at the target value.

Heat was generated inside the shroud using heating tapes with a resistance of 0.37 Ω/cm and a length of 240 cm, resulting in a temperature rise across the lens barrel of up to 33 °C. Each sensor reached the uniform temperature within 0.5 °C (standard deviation) after a period of 2 h after the stable electrical voltage was applied. The relationship between the applied voltage and temperature showed a well-characterized linearity with negligible hysteresis within 0.1 °C, and a gradient of 0.133 °C/V over the temperature range 22–34 °C. The change of 0.5 °C in temperature between the six sensing positions was small enough to show the satisfactory performance of our new athermal model, as our thermal analysis indicated that a 1 °C temperature gradient along the transverse and longitudinal directions would produce only a 5 nm rms degradation in the WFE.

The two side openings of the thermal shroud were closed to obtain uniformity in temperature across the LBS, and these were only opened for the interferometric measurements. After each WFE measurement was carried out, the side openings were closed to attain a temperature uniformity to within 0.5 °C to ensure the quality of the measurements. This process was repeated 10 times at a stable temperature before a new electrical voltage was applied, leading to the final WFE measurement data being averaged over 10 measurement points. A small electrical fan was used to circulate air to achieve a uniform temperature distribution inside the shroud; this was turned off during the WFE measurements.

Figure 5 shows the experimental results in terms of the Zernike coefficient corresponding to the defocus error. The data were recorded for ascending and descending temperatures, linearly fitted for each case, and then averaged. It is clear that the athermalization LBS achieved superior performance to the single LBS. The athermalization LBS showed an average defocusing gradient of 8.1 nm/°C, which is less than one-third the value expected from the single LBS (30.0 nm/°C). The measured gradient showed a difference of only 3.3 nm/°C from the theoretical expectation of 4.8 nm/°C. Such a difference is extremely small, considering the wavelength of the IR interferometer was 3390 nm. The very small difference in the gradients between the defocus error means that the LBS thermoelastic deformation had a negligible influence on the lens deformation. The experimental results, particularly the high linearity, imply that the sensitivity of the defocus error is likely to be valid over the lower temperature range of 8–20 °C.

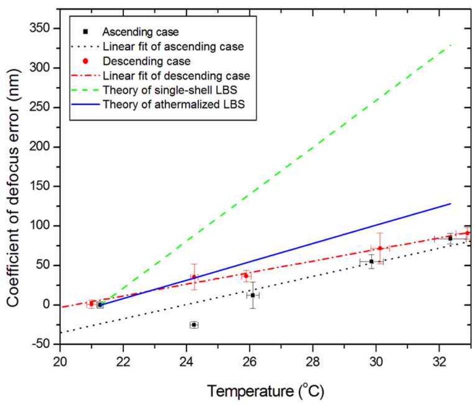

Fig. 5. Variation in the Zernike coefficient corresponding to the defocus error of the athermalization LBS.

With this new three-shell-based athermalization LBS incorporated into our design, the modal analysis showed a first natural frequency mode of 284.2 Hz. This frequency was confirmed by a low-level sine sweep. In addition, the optical performance of the LBS remained stationary before and after a random vibration test up to 47 G (gravity). This successfully shows that the three-shell structure using two materials with a large difference in CTE values provides a compact, but mechanically rigid solution for a satisfactory athermalization IROA that can be used in a vibration-rich environment, including airborne and satellite instruments.

5. CONCLUDING REMARKS

In this paper, we have described the design of an athermalized LBS consisting of three thin shells using two different materials with a large difference in CTE values in order to reduce the defocus error of an IROA optical subsystem. The defocus error was analytically and experimentally verified. As a result, the sensitivity in the LBS defocus error was reduced to 8.1 nm/°C, which is a big improvement on the theoretical value of 29.8 nm/°C of the conventional single-shell LBS. Our structure was shown to be rigid enough to withstand 47 G (gravity) in a random vibration test. This successfully demonstrates that this unique new three-thin-shell LBS (much improved from the original reentrant model) works well not only for satisfactory athermalization, but also as a practical instrument structure applicable for harsh operational environments seen in airborne and satellite missions.

5. REFERENCES

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