Proc. of SPIE Vol. 0250, Optomechanical Systems Design, ed. M. Bayar (Jan 1980) Copyright SPIE

Maintaining optical integrity in a high-shock environment

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Abstract

This paper examines various techniques, both optical and mechanical, that can be used to ensure system performance in high shock situations. From the optical viewpoint, this would involve optimizing system design to improve tolerance to such errors which are inevitable under operational conditions, and designing optical components that are not obviously going to be damaged by those same conditions. Mechanically, consideration must be given to methods of holding lenses, retainers, spacers, and of mounting mirrors and prisms that will provide the design location, as well as not damage the glass as the result of shock-induced elastic deformation of the metal parts.

Introduction

The optics referred to in this discussion are fairly large, long and complex systems, such as a folded path camera, or an extendable viewing/sighting system for an armored vehicle. The high shock environment is here limited to the 200 to 500-g range. While it is true that there are optical systems which operate in the 10, 000-g region, these are usually very simple optically, as in the case of missile tracking heads.

CAI has long been a supplier of complex, high-performance reconnaissance cameras, and is well known in this field. Less well known is that CAI has designed and built numerous reconnaissance viewfinders, including those for such carrier-based aircraft as the reconnaissance versions of the F8F, AJ, F7U, F3H, F8U and the RF-4B. In recent years, CAI has also designed and built sights and head-up displays (HUD) for a variety of training and combat aircraft, including the F4J. In parallel with this, the company has designed and built viewing systems and sights for armored personnel carriers and tanks. Figure 1 shows several viewfinders, while figure 2 shows a typical viewfinder optical system.

Experience with the aircraft-mounted systems provides the background to, while the lessons learned from the tracker/armored vehicles form the basis for this discussion.

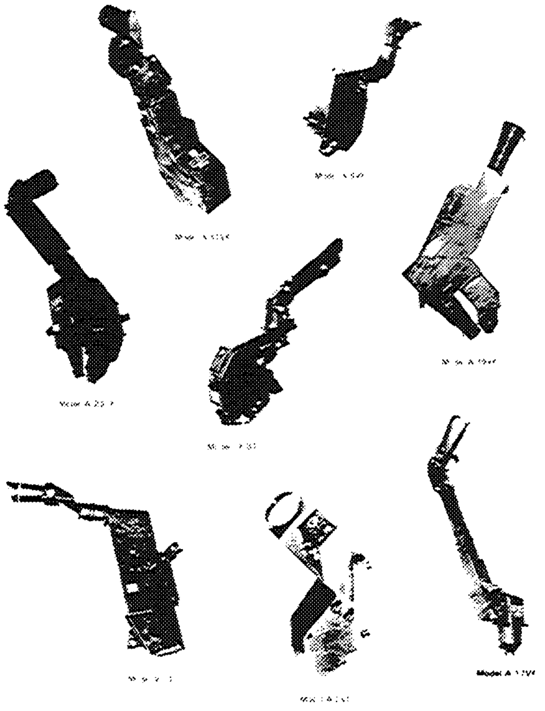

FIGURE 1. VIEWFINDERS

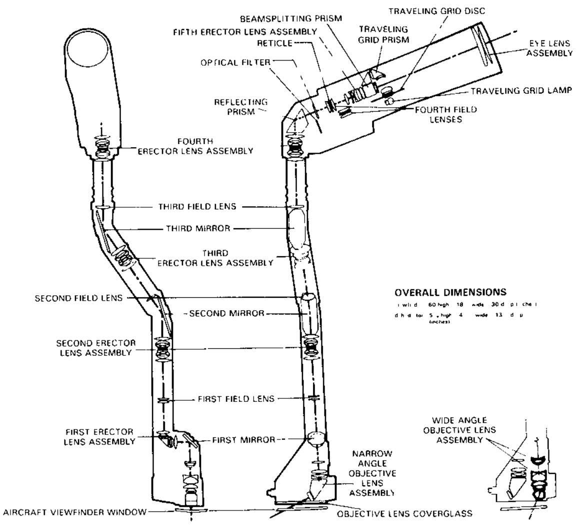

FIGURE 2. TYPICAL VIEWFINDER OPTICAL SYSTEM

Adverse Operational Conditions

Assuming an adequate optical prescription, there are very many conditions which can affect, all adversely of course, the predicted performance of an optical device. Some of these occur when design compromises are imposed by topographical features. Some result from imperfect material such as nonuniform index of refraction and residual strain caused by poor annealing or improper cooling, all of which tend to be beyond the influence of the designer. Then there are errors of form, either as incorrect radius, or the presence of any at all; incorrect centration; out of square prisms; wedge in windows; less than flat mirrors. Though these can be held to a minimum by careful tolerance distribution, the statistically improbable worst case will occur with alarming regularity.

Three other conditions which seriously degrade performance are errors in element spacing, nonperpendicularity of elements to the optical axis, and eccentricity of optical elements to the optical axis. Whether any or all of these conditions occur as the result of poor tolerance budgeting, thermal effects, or operational dynamics, i.e. vibration, acceleration or shock, they fall squarely into the area of responsibility of the designer.

Effect on System Performance

Operational experience as well as extensive computer analysis has enabled CAI to establish, in general terms, the relative effect of these three errors on system performance, both as isolated conditions and in various combinations. The operational experience was obtained by careful examination of assembled (field tested) units to determine, as nearly as possible, the actual position of the various optical components at the time of initial performance testing, and then after field testing.

The analytical method requires very careful preparation. Applying all three conditions to systems consisting of anywhere from thirty to sixty individual glass elements provides a situation where an almost infinite volume of data would be produced. Consequently, some perhaps arbitrary limits were imposed. Computed results were only printed when system aberrations reached values that were considered to be objectionable. These conditions are divided into two groups: those which affect the center of the field of view, such as spherical aberration, chromatic aberration and coma; while more liberal limits were established for field curvature, astigmatism and distortion as these tend to affect only the edge of the field. Emphasis was placed on the center of the field of view because the systems in question are used as aiming devices, thus field edge performance is considerably less important.

Examination of field-tested units was unexpectedly disappointing. Other than an occasional prism or mirror coming adrift due to faulty adhesive processing (which seriously affected optical performance), the only damage of consequence was the reduction of thickness suffered by plastic shims used as lens spacers, and some minor fretting of glass-to-glass and glass-to-metal junctions, where the contact was narrow, as in the case of a retaining ring, or where two elements are in edge contact as is shown in figure 3. The damage appears to have resulted from motion of cyclic nature, sustained vibration, rather than shock. The result of this damage was to permit minute variation of element spacing and occasionally some slight perpendicularity error. The effect on performance was quite negligible. Most of the units examined remained within the production tolerance range.

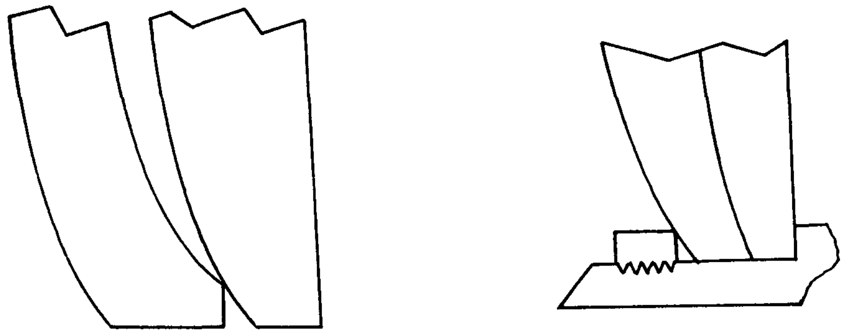

FIGURE 3. EXAMPLE OF MOUNTING TECHNIQUE THAT RESULTS IN "FRETTING"

It was hoped that the analytical method would produce definitive indications as to which of the conditions, spacing, eccentricity or nonperpendicularity, was the most significant, and if at all possible, establish some meaningful (mathematical) relationship between them. Because every system is unique, this did not happen, though conclusions of a general nature can be drawn.

Thought it may seem obvious, the power of a surface (or of an element) greatly influences the effects of any mispositioning of that surface. This is frequently overlooked, as can be deduced from sometimes frantic efforts to locate the flat windows. With this in mind, the relative importance of these mispositionings, in ascending order, is element spacing, element eccentricity and element nonperpendicularity, though the latter two are quite close in net effect. This is shown in figure 4.

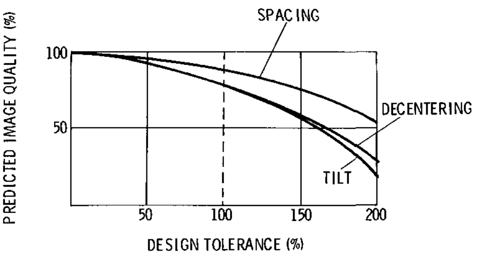

FIGURE 4. RELATIVE EFFECT OF GEOMETRIC ERRORS ON PERFORMANCE

Solutions

With this knowledge in hand, some quite positive steps can be taken during the layout phase of a system to either locate most of the "sensitive" elements and/or component groups so as to minimize the effect of transient loads, or to locally "harden" the structure. The discussion does not address the problem of element fracture, as that is usually the result of poor basic design. The significance of installing optical elements along the axis of disturbance cannot be exaggerated since it is the cheapest solution. Regrettably, it is also a rarely available luxury. This axial condition is demonstrated by telescopic rifle sights able to withstand recoil impulses of the order of 500 g indefinitely, but are easily destroyed by being dropped on their side.

However, circumstance and vehicle designers tend to conspire against simplicity. Figure 5 illustrates a system mounted on a tracked vehicle. This system is normally carried in a stowed position atop the vehicle, and it is erected for use. It provides viewing/aiming capability only when it is erect. Though not subject to gun-induced shock, it suffers considerable abuse while being ferried in the stowed position. Obviously, almost the entire optical train is very nearly perpendicular to the shock axis when in stow. Figure 6 shows a system which mounts directly to the elevation trunnion of a high velocity 7.5-cm gun. In addition to rotating with the gun in elevation or depression, the head travels with the gun during erection or retraction. The system provides search or aim capability in all positions. It is subject to attenuated gun recoil shock as well as road shock loads.

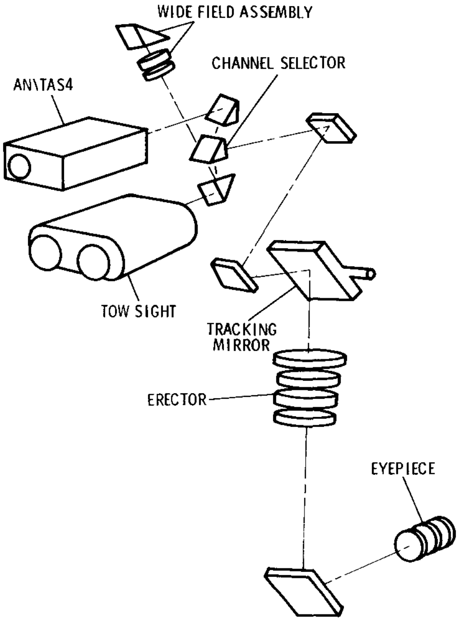

FIGURE 5. IMAGE TRANSFER ASSEMBLY

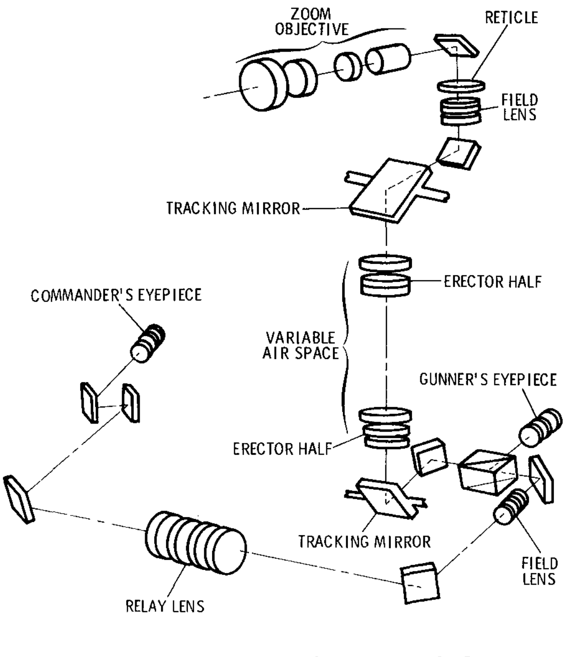

FIGURE 6. TANK-MOUNTED SIGHT (EXTENDABLE)

While on the subject of shock, a point that frequently gets overlooked during the design phase is the rebound from a shock impulse. This can on occasion be more severe than the initial blow. As an example, the system illustrated in figure 7 is carried on firm rubber pads, but the retaining latches are not cushioned. While this does not amplify the shock, it certainly sharpens things up.

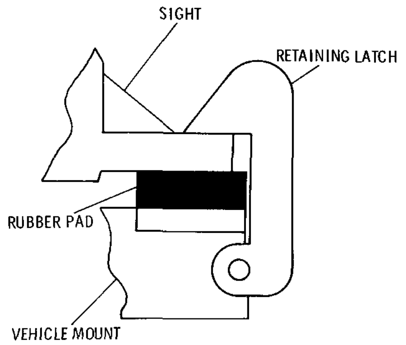

FIGURE 7. EXAMPLE OF POOR MOUNTING

Mounting Techniques

The mounting of optical components can be loosely divided in two groups: one includes mirrors and prisms, while the other would cover lenses.

For prisms and/or mirrors, the main considerations are sufficient rigidity and strength to maintain alignment. If adhesive is used, adequate area is an obvious requirement. Less obvious, in the case of elastomeric adhesives, is the hazard of a glue line which is too thick. In addition to the possibility of introducing distortion (bulk modulus effect), the rebound impulse imparted to the mirror may exceed the design limit of the bond area. Wherever possible, mounting points should straddle the component center of gravity. All rotating parts, such as tracking mirrors, should be statically balanced. It is assumed that devices revolving at high rates are both statically and dynamically balanced.

On the subject of tracking mirror drives, CAI has virtually abandoned gearing for such applications, having run the gamut of quality gearing to so called antibacklash gearing. The smooth drives were too loose, the tight ones very coggy. A preferred technique is to use thin metal drive bands or belts. They can be made thin to accommodate quite small drive drums, wide to carry the load, preloaded to ensure nonelasticity and tuned to render them immune to cyclic excitation. Figure 8 shows a typical drive, this one with a 2:1 reduction.

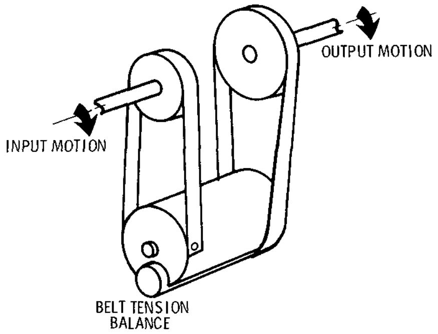

FIGURE 8. TYPICAL TAPE DRIVE (2:1)

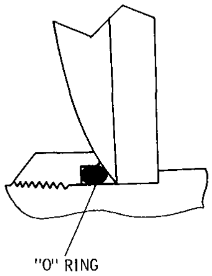

FIGURE 9. LOCATION AND SEALING

The various mispositioning errors tend to affect each other, and must be dealt with as one problem. The least serious error, lens spacing, is best done simply. The use of plastic spacers or shims is asking for trouble, as both tend to cold flow. Not only does this destroy spacing, but, in a worst-case situation, it can also introduce substantial lens tilt (nonperpendicularity) if the cold flow is uneven. Nor is spacing between threaded rings very secure. Maintaining the squareness of shoulder-to-thread axis is both difficult and expensive, especially in the case of thin narrow rings. Another characteristic of such rings is that they tend to back out of engagement after repeated heavy shock impulses. Lenses should be mounted against solid shoulders. Where threaded rings are used, the screw thread fit should be sufficiently loose to ensure that the lens is held against the shoulder reference. Of course, the ring must be securely liquid staked. A common requirement for such systems is that they be pressurized. The sealing is frequently attempted at the front element and is almost universally unsuccessful. If the "O" ring or gasket is sufficiently soft to provide a good seal, it will also permit the front element to shift under pressure; if it is of sufficiently high durometer to prevent this, it will probably not provide a seal. Figure 9 illustrates one successful approach to this problem. Note that lens location is independent of sealing arrangement.

More difficult by far is the problem of axial location. Two principal considerations conspire against success: thermal expansion coefficient differential and manufacturing tolerances. The first mitigates against tight glass-to-metal fit, the second virtually excludes such a fit. There are certain ferrous and nickel alloys with coefficients which closely approach that of glass, but all share the same disadvantages: high density, high cost and poor mechanical as well as machining characteristics. Thus, for all practical purposes, the designer is restricted to traditional materials such as steel and aluminum alloys. This has led to considerable experimentation (frequently unintended) in the search for the perfect method. There is, of course, no such condition.

Mention was made earlier of the rebound impulse. This can be as great as the primary shock impulse, and, obviously, is most serious on portions of the train which are perpendicular to the axis of shock. This requires that extra pains be taken to ensure adequate structural rigidity so as to minimize destructive elastic deformation, and possible residual resonance. The importance of this cannot be exaggerated.

But, in the final analysis, each lens element has to be dealt with individually. It might be concluded that very small elements, because of their low mass and inertia, would be the most easily dealt with. Unfortunately, the small elements require greater care in centering than much larger components: a .002 inch eccentricity on a .500-inch diameter element is proportionately far more influential than would be the same error on a 5.00-inch diameter element. A technique found quite effective for such lenses is to require good mounting bore concentricity coupled with relatively generous radial clearance. Small metal shims are used to center the lens, which is then retained with a nonrigid adhesive "ring". Note the distinction between nonrigid and elastic.

Large elements are mounted using a variation. Centering is achieved by three equispaced screws acting on the periphery of the lens. Small pools of the nonrigid adhesive are introduced around each screw. The screws should not bear directly on the glass, but on small metallic pads. Axial retention is kept independent of radial, the preferred method is an intermediate ring which conforms to the lens shape, the retainer. This has the benefit of cancelling thread eccentricities. Figure 10 illustrates this technique. There have been attempts at mounting large elements elastically, for instance on an "O" ring, or a cushion of silicone rubber adhesive. For many reasons, none were successful, and all were replaced by more conventional mounts.

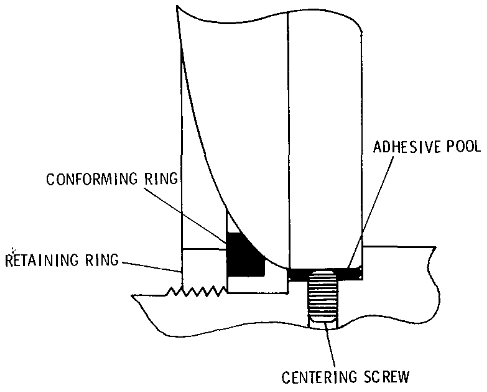

FIGURE 10. MOUNTING OF LARGE ELEMENTS

Conclusion

No paper of this nature can hope to offer solutions to all problems, and it would be presumptuous to attempt to do so. Rather, it is a compendium of conditions to be considered, and of solutions that have worked. Certainly, other approaches might also have worked. There is, of course, no guarantee that any or all of the previously successful solutions will work next time, which is why the profession of designer remains interesting.