Technical Report Synopsis:
Chapter 4: Mounting Individual Lenses
'Opto-Mechanical System Design'
Paul R. Yoder, Jr.

Introduction

Chapter 4 of 'Opto-Mechanical Systems Design' by Paul R. Yoder, Jr. is an introduction into mounting 10 – 250 mm (.4 -10 inch) optics. It provides techniques, suggestions and considerations for opto-mechanical and optical engineers whom are tolerancing the opto-mechanical an optical design. Yoder's topics are based off of creating what he considers the "Universally Preferred Lens" system. It is described as a lens that has minimal manufacturing and assembly tolerances, whose environment does not affect the location of orientation of optics and whose optical performance is not affected by the mechanical mounting. To achieve this type of system he describes optical centering, cost implications of manufacturing, the center of gravity of a lens, types of mounting techniques and the assembly and alignment of a lens to a cell or mount. This summary provides an overview of the chapter which introduces optical engineers about the reality of physical optical systems vs. theory.

Considerations When Mounting Optics

Optical elements are generally defined by an optical axis, for rotationally symmetric optical elements. The optical axis defines the reference location of the lens' best performance. An entire optical system is defined by an optical axis, sometimes called a line of sight. But this optical axis is not always concentric with the mechanical axis of the optical element. Most of the time optical elements have a wedge, α , that results in a decenter, δ , of the optical axis. This wedge happens because of material properties and/or manufacturing errors and tolerances.

The optical performance of a "universally preferred lens" is usually the limiting factor of most optical system designs. The mechanical parts do have manufacturing tolerances, but are generally more a economically limiting factor than a performance limiting factor. For a single element system, that will usually be mounted into a larger optical system, it is ideal to align the optical axis with the mechanical axis of the mount. (In Chapter 5 Yoder discusses the alignment of multi-element optical systems). But since the optical axis is almost never aligned to the mechanical axis of the lens, the mechanical mount needs to be designed to compensate for the decentered optical axis while still providing a "universally preferred lens". Yoder provides techniques which can be used to try to achieve this. It includes mechanical referencing, preloading, compensating and alignment. These techniques all have their own affects that limit the ability of the designer to achieve the "universally preferred lens".

For non-symmetrical optical elements, the optical axis, or axis of power of the element, should be defined and used as the reference for the mechanical design. The implications of mounting techniques become more complicated for non-symmetrical optics. The non-symmetric geometry/power distribution of the system makes it more difficult to disperse the mounting problems, such as stress, over the entire element or the axis of power of the element. For these types of systems it is recommended to perform perturbation of the tolerances to analyze and understand how the mounting techniques could affect the performance of the design.

In this chapter Yoder is considering mostly glass optics, but plastic optics can use similar techniques but there are some advantages and disadvantages. They are made by conventional grinding, polishing, molding and precision diamond turning techniques, depending on the material. Plastic lenses can easily incorporate mounting features, such as bevels, to allow for ease of assembly and alignment. Types of assembly include solvent bonding, heat staking and sonic welding. But they are limited in size, as the ideal edge to center thickness ratio should not exceed 3:1. Also large lenses can lead to less homogenous lenses if they are not injection molded properly.

The Balancing of Cost and Tolerances

An optical engineer should fully understand not only how the optical design will affect or limit the mechanical design but also how it will affect the budget. Yoder's "universally preferred lens" balances the cost of a high performing lens, it should be manufacturable and economical. In section 4.3 he summarizes multiple studies that provided data on the cost impacts of specific optical tolerances.

The base cost of an optical element is the sum of the labor, tooling, and test equipment associated with manufacturing an optical element. Tight tolerances increase the base cost but loose tolerances increase the mechanical and assembly cost. What makes the balancing act even more difficult is the fact that the tolerance/cost is not a linear scale and is dependent not only on the attributes of the lens but also on the optical shop itself. A couple studies that seemed the most important for an optical engineer are shown in figure 1.

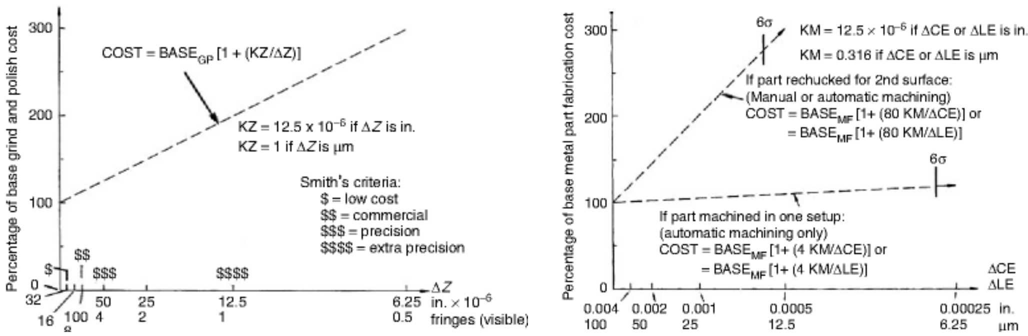

Figure 1) Graphs define the cost impact of a tolerancing the radius of curvature(a) and the concentricity tolerance of the optical axis to the mechanical axis(b)

An optical engineer should fully understand the tools and capabilities of the optical shop that is manufacturing their lenses. All the studies showed some variance in data which can be attributed to the different optical shops and their skill level as well as available tools. There also a mechanical cost with a similar association to tolerance, as tolerances tighten the cost goes up with a non linear trend, and is also based on the skill and tools of the machine shop.

Mechanical Properties

When mounting the individual lenses into a larger system the single optical system should have a calculated center of gravity and weight. These are important properties for qualifying a mechanical design based on specifications. To approximate this, a lens can be separated into spherical segments, circular cylinders and truncated cones (caps, disks, and cones). Weight and Center of gravity can be approximated by some simple geometric equations based on the simple shapes. The Center of gravity can be approximated by the following equations 1 through 4. Today though lens design software can calculate the lens weight for you.

$$X_{DISK} = L/2 \quad \text{Equation 1}$$

$$X_{CAP} = S(4R-S)/[4(3R - S)] \quad \text{Equation 2}$$

$$X_{CONE} = 2L[(D_1/2) + D_2]/[3(D_1 + D_2)] \quad \text{Equation 3}$$

$$X_{LENS} = \sum (X_i' W_i)/W_{LENS} \quad \text{Equation 4}$$

Techniques for Mounting

Low Precisions Mechanical Mounting

The decenter of the optical axis from the mechanical axis can be upwards of 30 arcmin, the optical axis could have abound 0.25 mm of decenter for low precision optics. Most likely there is a limiting factor besides performance for low precision optics, cost can be one of the main factors of this.

Spring Mounting

This mounting entails the optical element being supported by minimal contact of spring like elements. This type of mounting will still maintain the optical axis under some extreme conditions. It Has been used for optics that require cooling by air flow.

Burnished Cell Mountings

A metal lip is deformed after placing and aligning the element in the housing. The lip acts as a retaining ring and minimizes the movement of the lens. For this technique, the metal must be malleable, which means it should have a low Young's Modulus and low CTE and thus is not ideal for harsh environments. It is recommended to use a interface between the glass and metal to reduce the stress of differences in CTE and interaction of metal on glass. The lens can be subjected to large amounts of forces that could damage or break the lens during the burnishing process. It is ideal for mass production designs, plastic mounts designs and assemblies that will not be disassembled.

Snap Ring Mountings

Low performance application that provide simplicity in assembly at a low cost. The main issues with this technique, though, is the unpredictability of the axial preload during and after assembly.

Higher Precision Mounting

For high precision mounting usually the mechanical surface is in contact with the radii of the lens and allows the tolerances to be dependent on the optical surface, and in turn can reduce the cost. If it is cost effective the lens diameter can also be ground down to a cylindrical surface. This will keep the lens from jamming when there is a close fit between the diameter of the lens and the housing, and can also be a boundary for epoxies.

Types of Surface Interfaces

Sharp Corner

Contact between a lens and a corner of a machine part. It is usually not a knife edge due to machine shop practices of applying a 0.002 inch (0.05 mm) radius to edges.

Tangential

Interface of a mechanical surface contacting the spherical lens surface.

Torodial

Mechanical surface is torodial or donut-shaped, the radius varies between –R/2 to –R/32, where R is the radius of the lens. It is useful for concave surfaces where a tangent face is not possible.

Spherical

Mechanical surface is ground and lapped, usually with the optician equipment, to match the radius of the lens. Provides low contact stress over high preloads, can withstand high acceleration loads, and has good heat transfer properties (depending on the material). But is very expensive for manufacturing and testing.

Bevels

Good for contacting and protecting a lens. See figure 4. Flat bevel should be perpendicular to the optical axis, it defines the decenter of the lens if used as mounting surfaces. Angled and Step bevel are usually used for meniscus lenses. The step bevel is used as a reference while the 45^0 bevel is used for protection, no force should be applied to it.

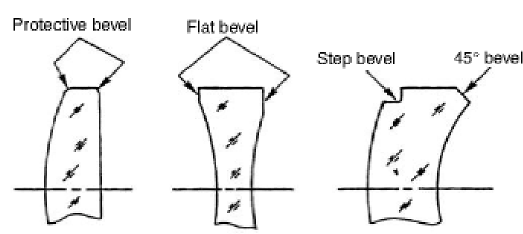

Figure 4) Types of Bevels

Cemented doublets uses a "step" bevel by making one of the lens diameters bigger than the other. The larger diameter acts as a mounting "step", providing better alignment movement than if the lenses were cemented by referencing their mechanical axis.

Mounting Techniques

For spherical surfaces the axial preload, P, to the optic is very important, as it can induce stress that could degrade the performance or even fracture the optic. It is important to characterize and control it when mounting precision optics.

$$P = (W_{a0}/\mu)\cos^2\theta \text{ , where } \theta = \arcsin(y_1/R_1) \quad \text{Equation 5}$$

Threaded Retaining Ring Mounting

Ring should be a different material than the barrel being used, or lubrication can be used but it is not ideal for optical systems. The ring should rattle on threads when the lens is not loaded, verifying that lens will not be subject to the extreme forces caused by a tight fit. The pitch of the thread should be no smaller than p where f_s is a safety factor and S_Y is the yield stress of the metal, D_T is thread pitch diameter.

$$p = 0.196 f_s P/(D_T S_Y) \quad \text{Equation 6}$$

Continuous Flange Mounting

Used for large optics 6" (15.4 cm) or larger in diameter, where a flange is in contact with the entire diameter, outside the clear aperture, of the lens. The flange can be either constrained by multiple screws threaded through the flange into the cell or held by a threaded cap. It is recommended to use a spacer between the metal interface and the flange to provide a more exact preload.

Multiple Cantilevered Spring Clip mountings

Clips ,or small flanges, are evenly distributed around the lens or in front, outside the clear aperture of the lens. Usually only three clips are used, but more can be used for a more even stress distribution. The clips can be tilted, using tilted washers, for a lens with a small radius. Spherical pads can also be used on the end of the clips to increase the contact surface area between the lens and clips.

This technique can be used on non-symmetrical optics, such as cylindrical optics. The clips should be evenly distributed across the surface to apply minimal loading stress to the optic.

Elastomeric Mounting for Lenses

Epoxy mounting should be fully investigated before choosing it as an option.

An elastomeric material allows the distance between the optic and mount to be maintained even during harsh conditions, including the deformation due to gravity. This is done by having holes in the mount to allow the elastomeric material to expand outside the mount when the lens and mount expand within the volume of the elastomeric material, during increases in temperature or extreme environments.

A process should be defined to include preloading specs and precision jigs. The thickness and the surface area of the elastomeric dispensed between an optic and mount should be defined to limit the amount of induced stress induced during and after assembly.

There is two step process. UV epoxy, which cures very quickly with UV light, is used to set the lens in place. Then RTV is used as a final bond that holds the lens in position.

Flexures

Mechanical elastic mounts that can provide controlled relative motion for components. Usually three symmetrically located flexures will maintain optimal performance even during vibration, shock and temperature changes, while minimizing stress. It is an expensive but reliable technique.
Blades can bonded to the diameter of and optic and maintains alignment in the radial direction.
Slots can be cut on the inner diameter of the lens barrel creating flanges that are attached to the outer diameter of lens.

Alignment of Lenses to Mounts

The alignment process can be chosen based on the type of lens, lens mount and/or performance required. A reference position should be defined, either optically or mechanically before the alignment process is begun.

Mechanical Reference

The barrel is aligned to a rotational stage, a lens is place in the aligned barrel. The lens is then translated and/or tilted, manually, by a micrometer or even a vacuum chuck, until the optical axis is aligned to the rotational axis of the table, thus aligning the lens to the mechanical axis of the barrel. The optical axis can be verified by an autocollimator, point source microscope or even a Fizeau interferometer setup with a test plate.

Pinning Process

Dowel pins are mounted into a lower cell that is parallel to the rotating table. A lens mounted to an upper barrel, which has locating holes for the dowel pins, is translated around the dowel pins until the optical axis is aligned with the rotational axis. The upper cell is mounted in place by epoxy by the two step method described previously. The dowel pins are used as the mechanical reference for the top lens and their positioning should have a tight tolerance. A Fizeau interferometer is ideal for verifying the optical alignment.

Mechanical Referencing

The lens is set in a barrel, the mechanical axis of the barrel is aligned to the rotational axis of the table. A dial indicator measures the run out of the lens to measure the decenter of the optical axis. Set screws are used the shift the lens and a retaining ring is used to mount the lens in place. Since the dial indicator is using the run-out of the optical surface, the barrel step surfaces should be parallel so it does not add error to the measured run-out.

Precision barrel

A barrel with a tight tolerance is used. Not tip or tilt alignment is needed, just translation to align the optical axis to the mechanical axis of the barrel. The lens is usually mounted with an elastomeric material. A Fizeau set up or autocollimator can be used to verify the optical alignment with a reference axis.

If the lens is needed to have a specific diameter a Single Point Diamond Turning machine can be used, once the lens is mounted, to grind down the diameter of the lens.

The barrel itself can be machine to align the optical axis with the mechanical axis of the barrel. It is great for controlling multiple mounting surfaces accurately, and can easily align aspheres quickly. This type of alignment process can be expensive not only for the process but also the parts that go into.

Conclusion

In Chapter 4 of Paul R. Yoder, Jr.'s 'Opto-Mechanical System Design' he exposes the reader to the "universally preferred lens". It is a design that balances the optical performance with mechanical designs, environmental stability and cost effectiveness. The process for designing the universally preferred lens should be the main take away from this chapter. The design ideas and techniques presented should be investigated and understood before using them in a design. Yoder provides a list of references after the chapter that are great for opto-mechanical and optical engineers. While the "universally preferred lens" is not completely achievable, the design characteristics are what every engineer should strive for.