The Finer Points of Fine Mechanics – Design Consideration for Opto-Mechanics Part 1

Introduction

Finding the correct optical mounting solution for a specific application often requires consideration of more than just the basic specifications of posts and mounts. Basic specifications might enable some initial decisions, such as the choice of post material and the type of mount. However, reviewing basic specifications can lead to more questions than answers. So to ensure your mounted optics help you meet critical performance criteria, users must further consider numerous subtle criteria. This paper presents definitions, test data, and performance details for three important and nuanced optical mounting considerations: post holders, mounts, and mounting methods.

Posts

Beginning with the optical table, the first important components to understand regarding mounting optics are the post and the post holder. Typically, the post is steel and secured to the optical table by a clamping fork or a post holder, which is the interface between the optical mount and the optical table (some examples of these can be seen in Table 1). Although these components are often an afterthought, they can impact stability as much as the mount and optic they support.

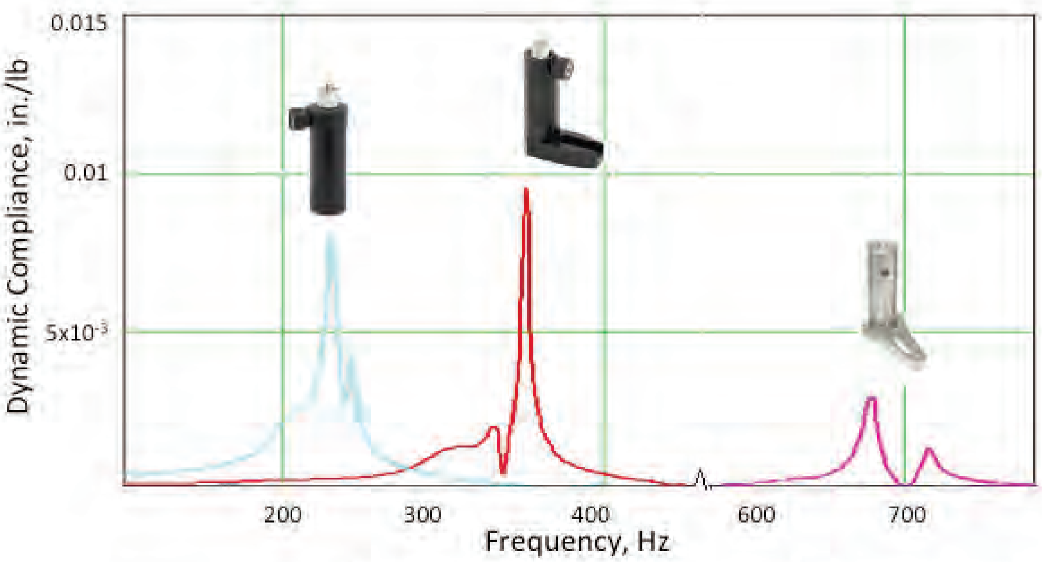
It is no surprise that large-diameter posts have more stability and deflect less than small-diameter posts under the same load. However, other factors to consider in selecting a post include material, geometry, and mount-contact surface area. Let's compare details of the three most common post types.

Post Type	Components	Table Mounting	Main Material	Fabrication/ Cost	Mount Contact Surface Area
 Standard Post	Ø.5 in. (12.7 mm) stainless steel post inside post holder	Single-threaded stud (¼-20 or M6)	6061-T6 Aluminum Alloy	Machining/$$	0.79 in² (5.1 mm²)
 Slotted-base	Ø.5 in. (12.7 mm) stainless steel post inside slotted-base post holder	Slotted base, clamped with socket head cap screw (¼-20 or M6)	A380 Aluminum Alloy	Casting/$	1.70 in² (11.0 mm²)
 Pedestal Post	1 in. (25.4 mm) stainless steel pedestal with 1¼in. (31.8 mm) base	Pedestal Clamping Fork	303 Stainless Steel	Machining/$	1.23 in² (7.9 mm²)

Table 1. Comparison of Standard, Slotted-Base, and Pedestal Posts

The standard and slotted-base post holders are actually two-part mounting systems consisting of a hollow external cavity (the post holder), and an internal bar (the post) that adjusts to a panoply of height and rotational positions. These two post types easily adapt to fit many setups. The slotted-base post combines height-adjustment versatility with a larger mount-contact surface area (the area of the optical surface that touches the mount – the more, the better), thanks to the manufacturing process that forms a post holder and a slotted base into a single unit.

The 1-in. diameter pedestal post is a fixed-height post. What it lacks in height adjustment, it makes up for in stability, owing to stiffer material and larger mount-contact surface area. Comparing the vibration response of the three post types reveals the design advantages and disadvantages of each (see Figure 1).



	STANDARD POST	SLOTTED BASE	PEDESTAL POST
RESONANT FREQUENCY PEAK	250 HZ	350 HZ	680 HZ
COMPLIANCE	0.0070 IN./LB	0.0095 IN./LB	0.0043 IN./LB

Figure 1. Post-holder dynamic compliance is featured as a function of resonance frequency for (left to right) standard, slotted-base, and pedestal post mounts. A higher resonance frequency and lower compliance are desirable.

When comparing the dynamic performance of the three post mount types, users should note the dynamic compliance and resonance frequency response of each. Dynamic compliance is the deflection property of the post, which is undesirable in posts, so smaller values are better. The resonance frequency is the frequency at which the post resonates in response to vibration of the system, which can affect optical stability. In an ideal design, you would want the lowest possible amplitude at the highest possible resonance.

The pedestal post (right) has the lowest compliance of 0.0043 in./lb (0.25 mm/N) and a resonance frequency of 680 Hz. When comparing the slotted-base (center) and standard post holders (left), the slotted-base has a 100 Hz higher resonance frequency because it's formed as a single part and has a larger mount-contact surface area. Users should take care to note the peak resonance frequency of a post with respect to the peak resonance frequency of the mounting surface since these components are bolted together to form a complete mounting system.

For example, a typical optical table has its own compliance curve and resonance frequency (see Figure 2). The compliance curve for a 4 × 8 × 1 ft. (1.2 × 2.4 × 0.3 m) optical table reveals three resonance zones: the first centered around 200 Hz the second around 300 Hz and the third at 500 Hz. For optimal performance in an optical experiment, the best mounting posts would exhibit resonance frequencies different from those of the optical table or platform being used.

Figure 3 compares the resonance frequency zones of an optical table with the three types of mounting posts. The individual resonance frequencies of the optical table and the standard post holder occupy the same zone. Therefore, vibrations in this zone would not only excite the table resonances but also the support resonances. However, the higher resonance frequency of the slotted-base post holder lies partly outside the optical table resonance zone, which is advantageous. A resonant table vibration would have a reduced effect on the slotted-base post holder. The pedestal post and clamping fork combo, in comparison, completely eliminates any overlap of resonance frequencies of the optical table, so would be the ideal choice in this situation. Certainly higher performance tables, which reduce the amplitude of these resonances, would also provide additional stability to the system.

However, not all users require optical mounts with the highest level of stability. Certain types of optics are more sensitive to misalignment and instability than others. The drift of reflective optics like mirrors and beamsplitters are especially sensitive to optical alignment. This is governed by Snell's Law, which states that the angular travel of an optical beam is twice the angular travel of the mirror itself. So, a 1-degree movement of a mirror will cause the reflected beam to move by 2 degrees. For this reason, users should mount mirrors and beamsplitters with the stiffer 1-in. pedestal posts because they have a higher resonance frequency and lower compliance.

Transmissive optics like lenses and filters are less sensitive to optical misalignment than mirrors.

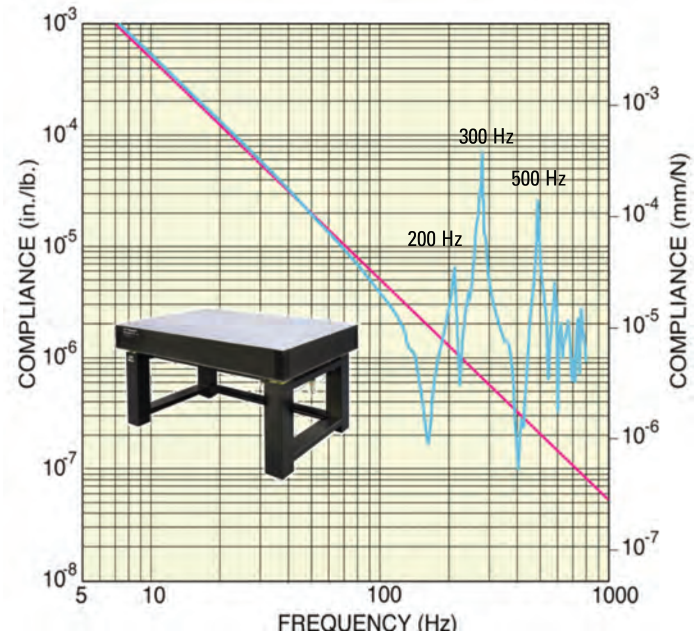


Figure 2. Compliance curve for a 4 × 8 × 1ft. (1.2 × 2.4 × 0.3 m) optical table shows its resonance frequencies.

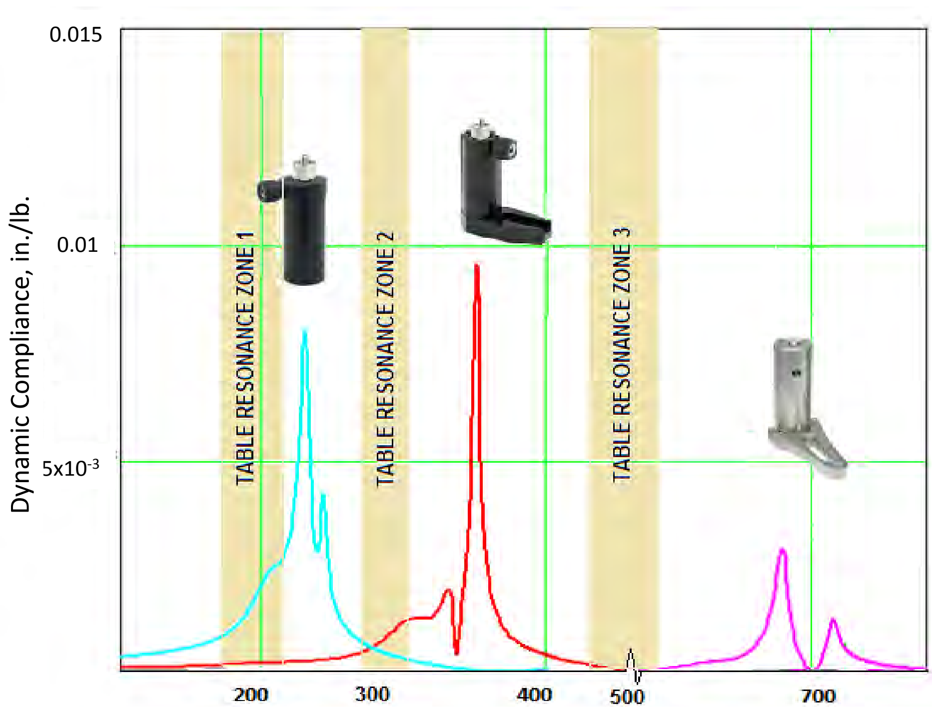


Figure 3. One resonance frequency zone of an optical table overlaps with standard and slotted-base post types.

The angular shift of a lens typically results in an image location shift, the magnitude of which is dependent on the focal length of the lens. Lenses with longer focal lengths will cause the image to move less. For this reason, lenses could be mounted with slotted-base post holders because they have a moderate resonance frequency. Filters are the least affected by optical misalignment and system instability. Thinner filters are less sensitive to misalignment than thick filters. Most filters can be mounted with standard post holders (see Table 2).

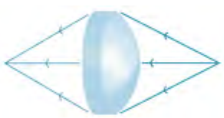
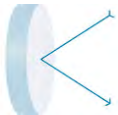
Optic Type	Recommended Post type	Examples	Cost
Filters 	 Standard	Newport VPH series Newport SPH series	$$
Lenses 	 Slotted base	Newport BPH series	$$
Mirrors 	 1-in. Pedestal	Newport PS series Newport Q-TMS series	$$$

TABLE 2: Recommended Post Types for Various Optics

Optical Mounts

The next consideration for your optical mounting needs is the mount, which is attached to the post and suspends the optical component in its place. Typical optical experiments and systems use multiple optical components such as lenses, filters, and mirrors. Because these components require alignment relative to each other, one of the key features of an optic mount is multi-axis adjustability. To facilitate this adjustability, optic mounts are constructed with intricate, high-tolerance parts. While these parts interact with the high precision needed to align optics, their different materials and geometries can lead to instability, especially in temperature-variant environments. Selecting a mount for a particular system or experiment requires understanding the basic magnitude and direction of thermal drift. In this section, we explore the thermal stability of different optic mounts.

Figure 4. The Newport CONEX-LDS electronic autocollimator measures optical deflection.

The thermal stability of a mirror mount, or any mount for that matter, is governed by its materials, geometry, and the fit of its mating components. Different materials expand and contract at different rates and in an environment of varying temperature, overall drift can occur. Because it is nearly impossible to mathematically predict the effect of heat on various materials with complex assembly geometries, we use an empirical approach to measure temperature-dependent effects. Of all the optics in an optical system, the mirror mount is the most sensitive to thermal instability and effects.

Thermal testing allows comparison of different types of mirror mounts. Thermal testing of a mirror mount involves several key pieces of equipment: a damped optical table, a thermal chamber, and an electronic autocollimator. The optical table is the foundation for the test unit and the test equipment. The thermal chamber allows precise temperature control of the test unit's environment. The electronic autocollimator measures the angular deviation of the mirror mount (see Figure 4).

Figure 5. Mirror-mount types include aluminum (Newport M1), 300-series stainless steel (Newport SU100-F2K), and low CTE stainless mirror mounts (Newport SX100-F2KN-254).

Mirror mounts are typically made from aluminum or stainless steel. Within the past year, however, a new generation of super stable mounts with low coefficient-of-thermal expansion (CTE) stainless steel has been introduced to the market (see Figure 5).

Stainless-steel mounts are stiffer making them easier to align and they exhibit better thermal stability. They are also more expensive, heavier, and require a longer thermal stabilization period than aluminum mounts (see Table 3).

	Aluminum	Stainless Steel	Advantage
Stiffness (Gpa)	69	200	Stainless steel mounts are stiffer and easier to align.
Thermal Expansion (μm/mK)	22	16	Stainless steel mounts have lower CTE and lower drift.
Density (kg/m³)	2700	7500	Aluminum mounts have lower density and weigh less.
Machinability	360%	45%	Aluminum mounts are easier to machine and cost less.
Thermal Conductivity (W/mK)	205	16	Aluminum mounts have higher thermal conductivity and stabilize faster.

Table 3. Properties of Aluminum Versus Stainless-steel Mounts

A thermal deflection test is the most meaningful way to measure the full effect of temperature change on the deflection of a mirror mount (see Figure 6). In a thermal deflection test, the temperature of the test chamber is elevated from ambient room temperature to approximately 10°C above ambient, then returned to the starting point. The angular deflection of the mount is recorded over time and temperature, where the yaw-axis deflection is measured separately from pitch-axis deflection.

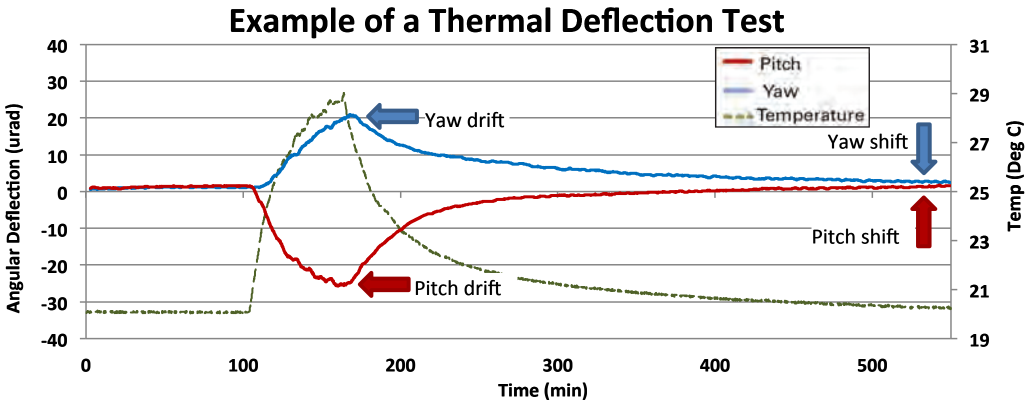


Figure 6. A thermal deflection test demonstrates how a mirror mount exhibits angular deflection over time and temperature.

The test reveals two key pieces of performance data: drift and shift. The drift is the maximum deflection of the mount over the duration of the test, which usually occurs when the test chamber is at its maximum temperature. In Figure 6, we can determine the drift values of the mount: in this example, pitch drift is 25 µrad and yaw drift is 20 µrad. Shift is a measurement of how well the mount returns to its original position following the thermal cycle. In our example, the pitch and yaw shift are about 2 µrad, which is indicative of a stable mount.

When this test is performed on the three types of mirror mounts discussed above, the effect of the different materials becomes clear (see Figure 7). As expected, the more expensive stainless-steel mounts outperform the aluminum mount in both drift and shift. Between the two stainless-steel mounts, the low CTE version deflected less overall than the standard 300-series stainless-steel mount.

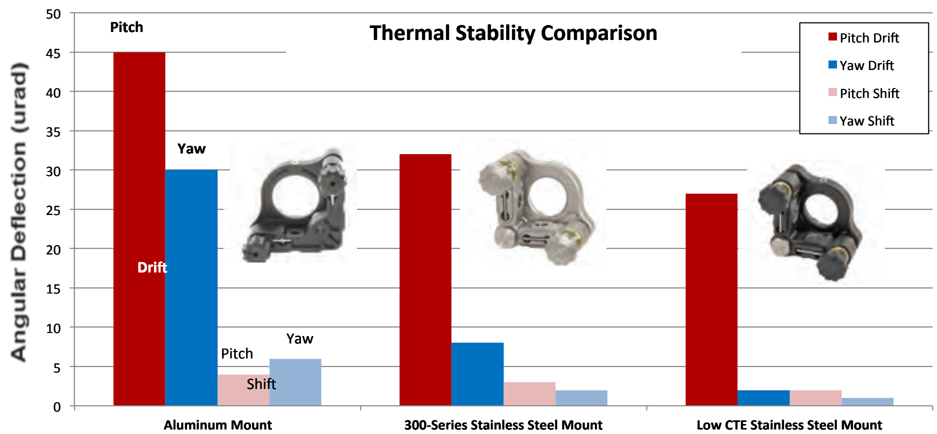


Figure 7. The thermally induced angular deflection of three mirror mounts reveals the behavior of aluminum versus stainless steel and low CTE stainless steel.

As with post mounts, not all applications using mirror mounts require maximum stability. Aluminum mirror mounts, though not as stable as the stainless-steel mounts, performed admirably in tests for various applications. Test results using aluminum mounts were within an order of magnitude of the stainless mounts, which are two to ten times more expensive than the lowest cost aluminum mirror mounts (see Table 4). The 300-series stainless-steel mount returned noticeable stability advantages over the aluminum mount, making it suitable for more demanding, high-stability applications. The performance of the low CTE stainless-steel mount was the best of the three mounts tested, having both the lowest drift and the lowest shift. The low CTE mount is therefore suited for the most demanding applications, such as laser tooling or industrial lasers. The low CTE mount is available with high sensitivity 254-TPI actuators to provide adjustment that is on par with its high stability.

Mount Material	Application	Examples	Primary Advantages
Aluminum	Beam Routing	 Newport M Series M1 and M1Q	Low Cost Horizontal Mounting
300-series Stainless Steel	Interferometry	 Newport Suprema SU100-F2K	Integrated Actuator Locks
Low CTE Stainless Steel	Laser Tools	 Newport XTE Suprema SX100-F2KN-254	Low Thermal Drift High Sensitivity 254-TPI Actuators

Table 4. Mirror Mount Recommendations by Application

Design Options

From a design standpoint, the two most common mirror mount types are kinematic and flexure. Kinematic mirror mounts have a movable frame that pivots on three ball bearings such that the first ball makes contact with the fixed frame at exactly three points, the second ball at two points, and the third ball at just one (see Figure 8). These six points of contact exactly constrain the six degrees of freedom for motion of the movable frame. With a flexure mirror mount, an elastic element provides the means for angular positioning of the mirror. A single-strip flexure bends like a cantilever and provides the guided rotation as well as the restoring force. Figure 9, below, depicts these two mount mechanisms. Kinematic mounts are widely used because of their adjustment range, easy-to-use adjustment knobs and also their availability. Contrast this to flexure mounts which typically do not feature adjustment knobs and offer less angular travel – but what they lack in features, they make up for in performance as many optical engineers are discovering.

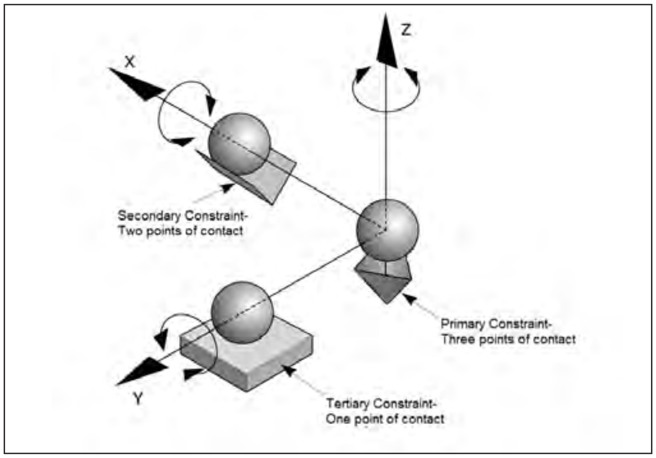


Figure 8: The kinematic mirror mount mechanism

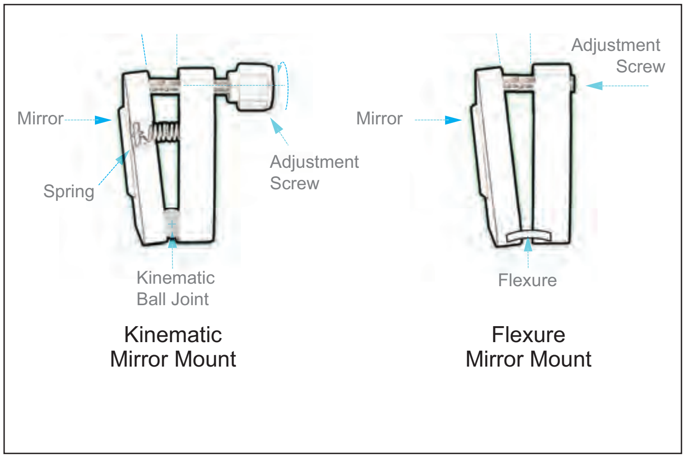


Figure 9: The kinematic mirror mount has a ball joint and spring; the flexure mirror mount is jointed with a welded flexure.

Recent studies reveal that flexure mounts might be some of the most stable mounts around - even more so than traditional kinematic mounts. Figure 10 compares the thermal characteristics of two like-sized stainless-steel mirror mounts; one with the traditional kinematic design and the other, a flexure design.

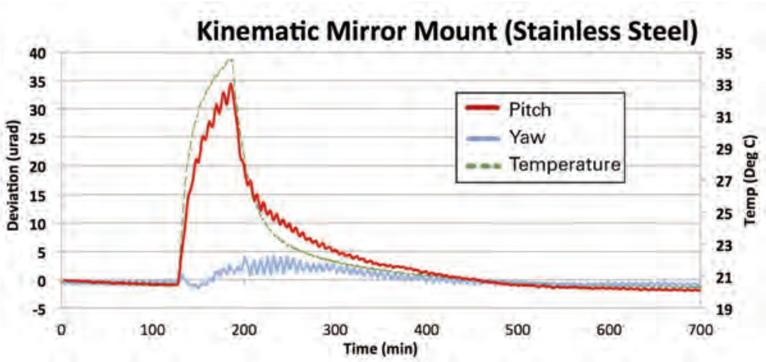


Figure 10a: Kinetic mirror mounts are subject to significant pitch-axis drift at high temperatures.

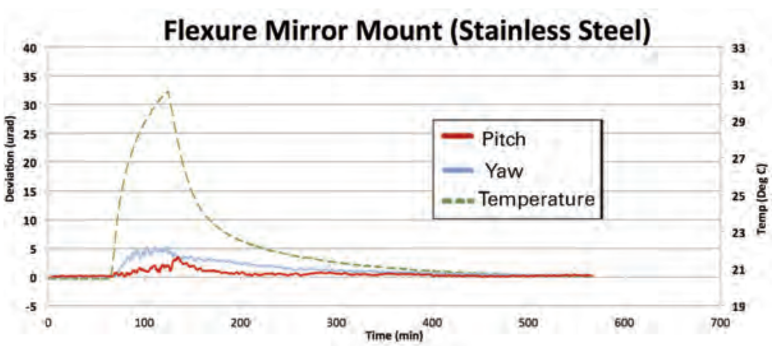


Figure 10b: Flexure mirror mounts are relatively stable at high temperatures.

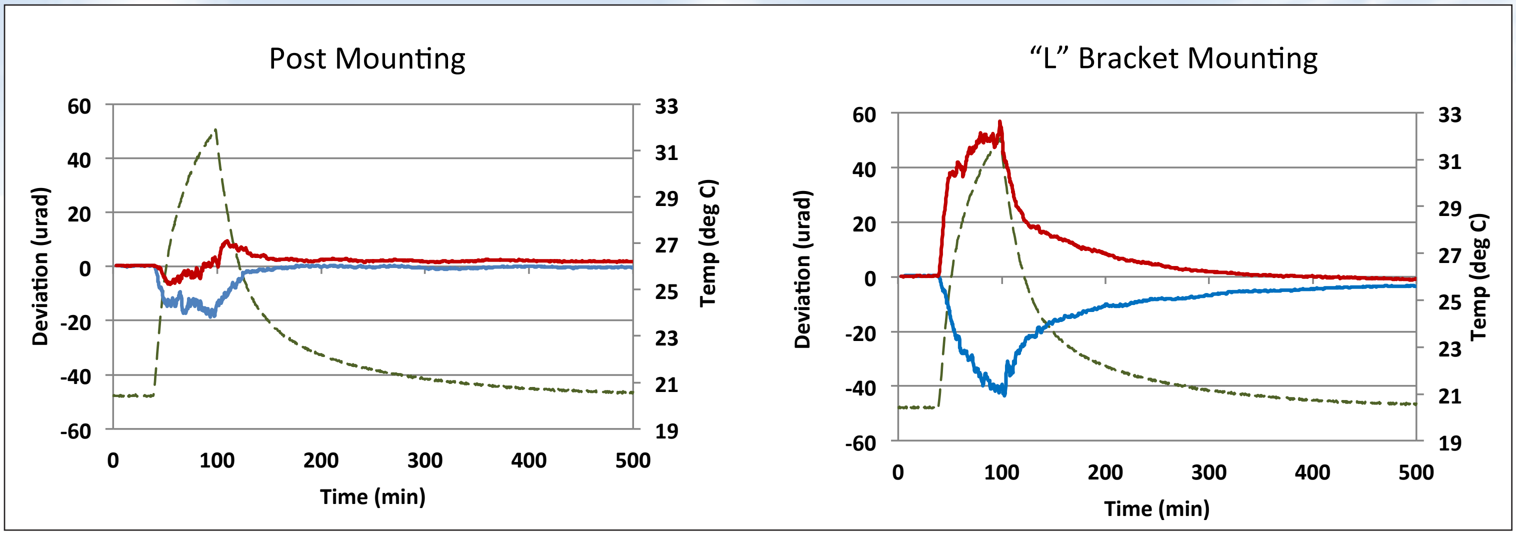


Figure 11: Thermal testing of a flexure mount with a post (left) and bracket mount (right) reveal that the bracket is the cause of drift deflection.

While the hysteresis performance of both mounts is excellent, the flexure mount has noticeably lower overall pitch-axis drift at maximum temperature. For example, at maximum temperature, the pitch deflection of the flexure mount is just 4 µrad, compared to 35 µrad for the kinematic mount. As stated earlier, mounting can have as much of an impact on stability as the mount itself and this is especially true of flexure mounts. Kinematic mounts use the 1- or ½-in. stainless-steel post for mounting but flexure mounts are designed for bulk-head or plate mounting. Figure 11 presents thermal drift test results of the same flexure mount using two different mount support types – a steel post vs. an aluminum “L” bracket. Mounting flexure mounts on flexible aluminum brackets can degrade their performance and cause engineers to make the wrong conclusion regarding mount performance.Since the same flexure mount was used in both tests, it is easy to see that the bracket alone is responsible for almost all of the drift deflection.

Optic Mounting Methods

Numerous methods for mounting optics exist mainly because the same type of optic can be mounted in several different ways. The established mounting methods are governed by the geometry of the optic and how frequently the optic needs to be changed or replaced. For example, a round convex lens requiring frequent replacement should be mounted with a three-point perimeter or v-groove mount. Mounting this convex lens in a permanent way would be done with a threaded retaining-ring mount (see Figure 12). Since the threaded retaining-ring mount holds the lens on its curved convex surface, it has the added benefit of automatically centering the lens in the mount. This feature helps considerably in the alignment process because the optical center line is accurately referenced to the post mounting surface.

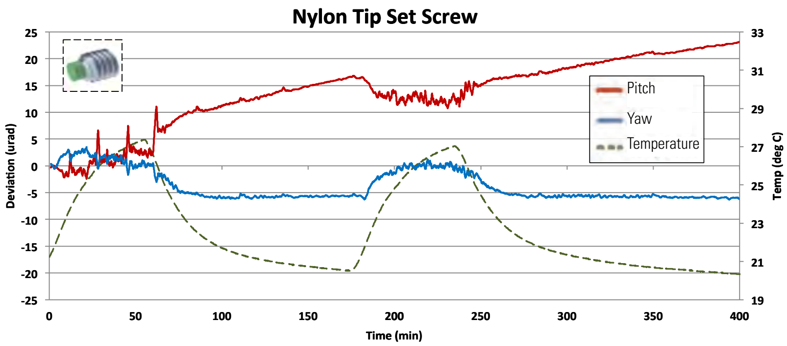
Compared to lenses, optical filters are less alignment-sensitive and therefore have more mounting options. Filters can be mounted in the same way as lenses; another option is the new EdgeGrip™ filter mount (see Figure 13). These unique mounts securely grip the filter on its lower edge, leaving the space above and to the sides clear of light-blocking structure. This design is the most compact of all filter mounts and has the capability of holding either round or square filters of various sizes and thicknesses.

Figure 12: Lens mount options include the three-point perimeter mount, the v-groove mount, and the threaded retaining-ring mount.

Figure 13: The EdgeGrip™ mount holds square or round filters of various sizes with minimal light blockage.

Although similar in shape to filters, mirrors have different mounting requirements. Alignment stability is a key requirement in mirror mounting. However, another equally important requirement for many applications is minimizing the optical distortion that is caused by mechanical stresses on the optic. Out of numerous optic mounting methods, the most common is the set-screw-enabled three-point method, which is popular due to its simplicity, low cost, and resulting stability. Mirror mounting relied on the three-point nylon-tip set screw almost exclusively for decades. But with ever-increasing stability requirements, oval-tip set screws are in common use today. The oval-tip set screw is simply an all-stainless-steel design with a smooth spherical tip. This tip style has distinct trade-offs against its nylon-tip counterpart: stability vs. distortion.

The oval set screw creates a slighly higher peak-to-valley wavefront distortion on an optical surface than the nylon set screw, which doesn't affect most applications. Notwithstanding the wavefront distortion, comparative thermal stability tests show that the oval set screw causes significantly less alignment hysteresis compared to the nylon set screw. Figure 14 shows the test results of a single mirror mount tested first with a nylon-tip set screw and then with an oval-tip set screw. The pitch axis of the nylon-tip fitted mount shows a clear drift in alignment that is not present on the oval tip mount.



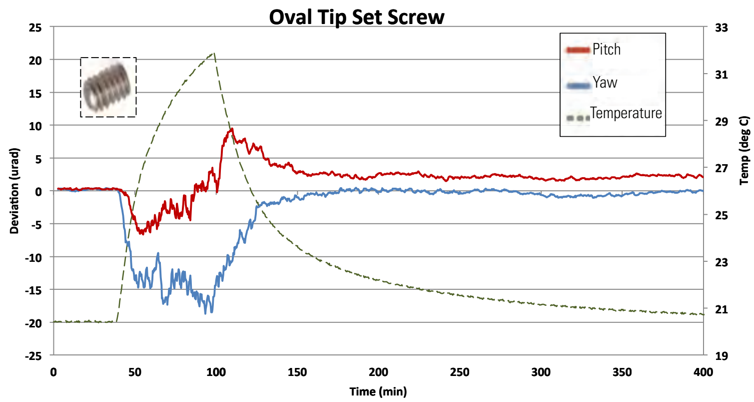


Figure 14a and b: Nylon-tip set screws are subject to more alignment drift at high temperatures than stainless steel oval-tip set screws.

The same characteristic of the nylon tip that provides the reduced distortion has the unwanted side effect of causing additional alignment drift. The compliance and deformation of the nylon set screw lowers the force on the mirror and likewise reduces distortion. But temperature fluctuations cause the compressed nylon between the screw and mirror's edge to move and shift the mirror's alignment.

Regardless of the chosen tip material in the set screw, most three-point mounting methods induce wavefront distortion, especially on larger mirrors. For applications requiring very low optical distortion, low wavefront distortion (LWD) optical mounts are an alternative design option. Low wavefront distortion optical mounts use an axial six-point mounting method to gently but securely hold the mirror (see Figure 15).

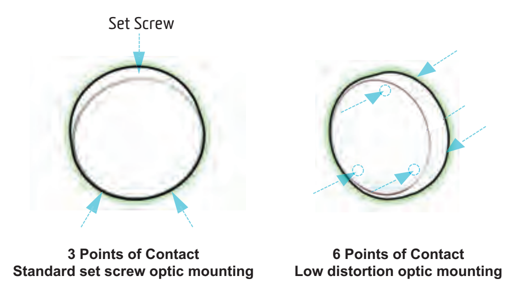


Figure 15. Set screws typically have three points of contact. Low wavefront distortion mounts have six points of contact.

The six-point LWD mount minimizes distortion not only because the forces acting on the optic are oriented axially and in line, but also because it has twice as many mounting points. The forces that would cause distortion are more distributed and axially opposite to eliminate bending. Interferometric testing verifies the benefits of the six-point mounting method (see Figure 16, shows examples of both an LWD mirror mount and an interferometer flatness test.

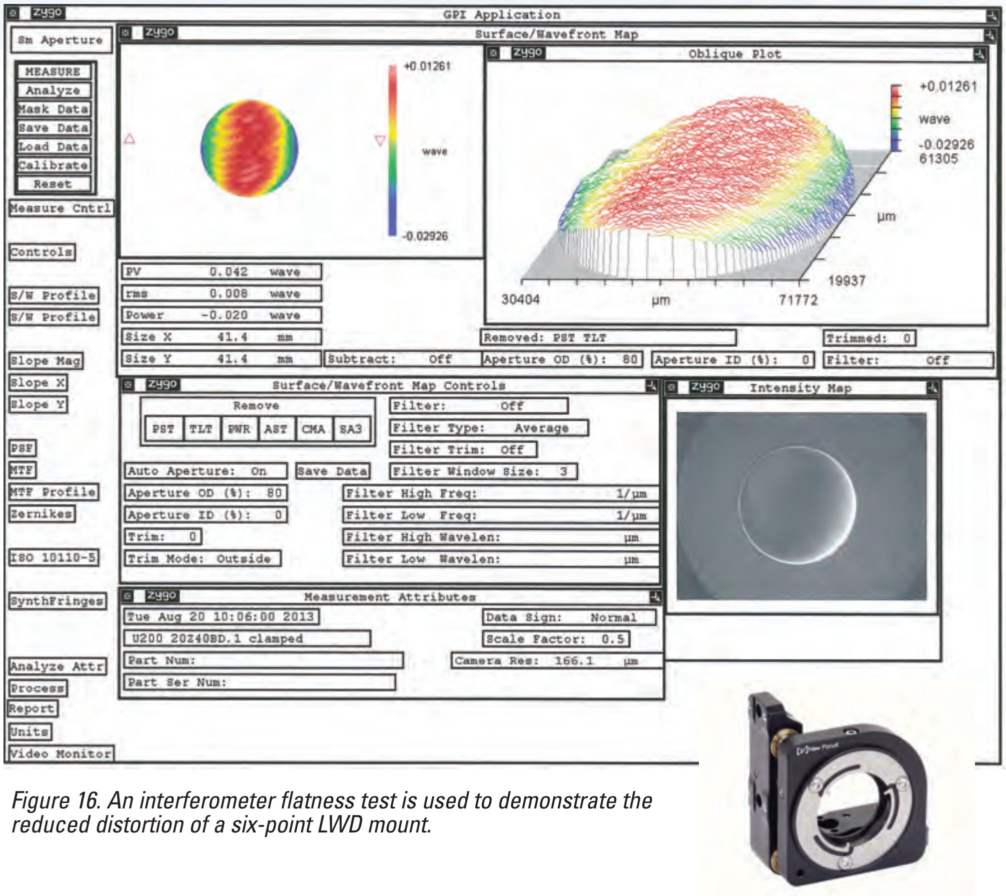


Figure 16. An interferometer flatness test is used to demonstrate the reduced distortion of a six-point LWD mount.

The test finds that the distortion difference between the unmounted and mounted mirror was only 0.03 peak-to-valley wave of 19.1 nm. In contrast, consider the flatness of a mirror mounted with the standard set screw, torqued to 8 oz-in. (see Figure 17). The LWD mounting method significantly reduces the wavefront distortion of the set screw mounted mirror from 0.34 wave to 0.09 wave, a 73% reduction.

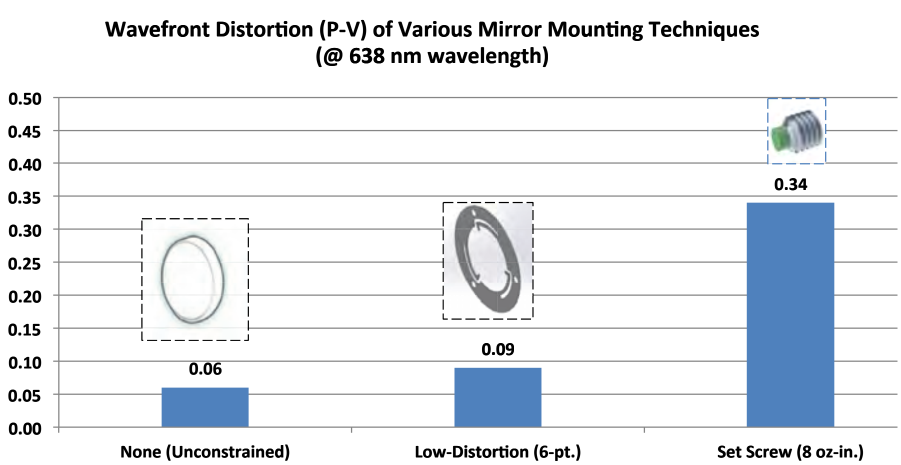


Figure 17. Wavefront distortion is significantly lower using low wavefront distortion mounting compared to set-screw mounting.

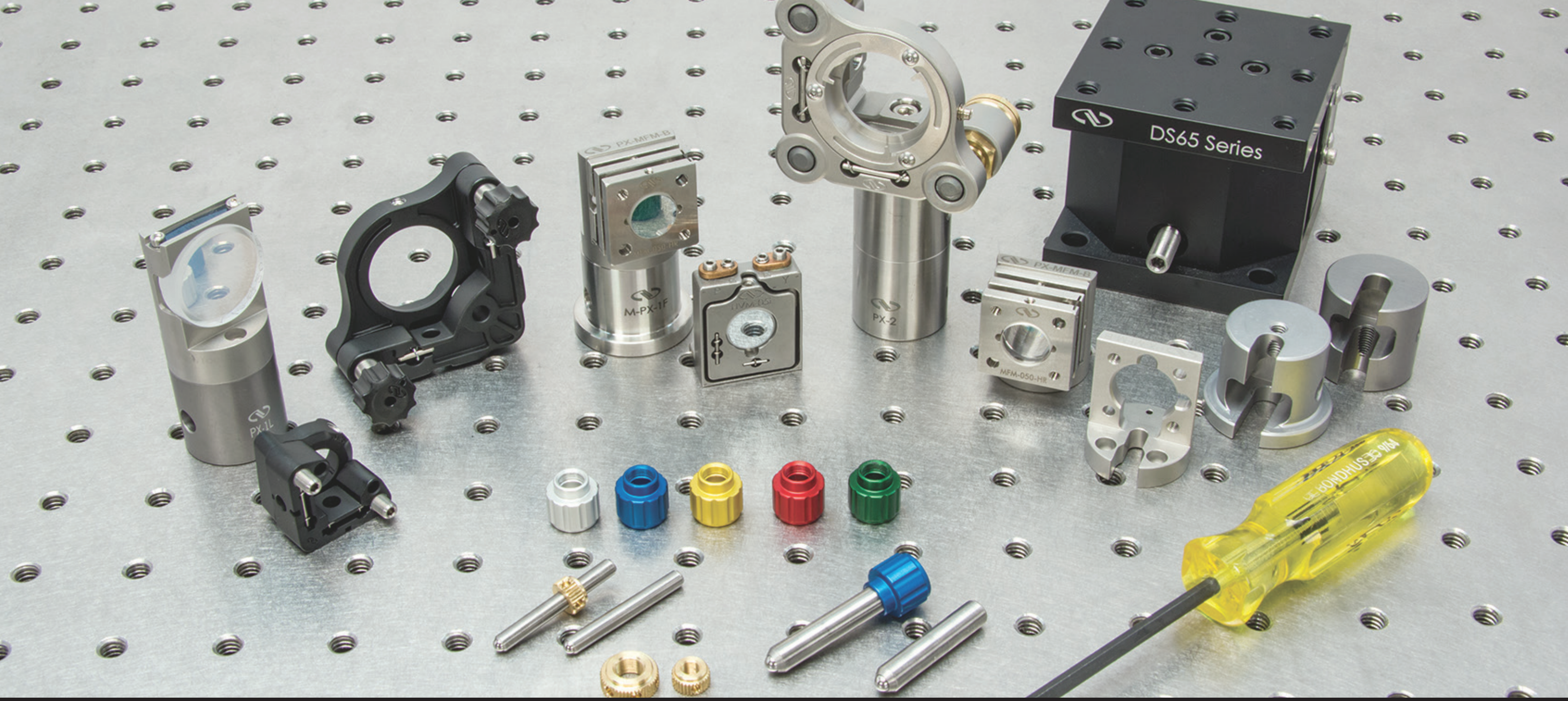
The benefits of the six-point LWD mounting technique are evident with regard to minimizing optical wavefront distortion. Still, users must consider the drawbacks of this design before deciding on this type of mount, namely larger size and cost. Because of the larger diameter of the six-point retainer, mirror mounts using them must also be larger in size. A larger size is almost never an advantage in most applications. The larger size, in addition to other things, also adds to the cost of these mounts. The cost difference between a standard set screw and a six-point mirror retainer weighs significantly in the overall cost as well.

Conclusion

Although the options are numerous for post holders, optical mounts, and optical mounting techniques, understanding even a little more about the performance characteristics of these components can reduce the uncertainty in the selection process.

- With the evaluation of post holders, the pedestal post has lower compliance and higher resonance frequency, while the slotted-base post holder, formed as a single part, has a larger mounting surface area and a higher resonance frequency than the standard post holder.
- The thermal testing of aluminum and stainless-steel mirror mounts show that the low-CTE of the stainless-steel mount allows half the deflection in yaw of its aluminum counterpart. The flexure mirror mount displays impressive results in the thermal stability test and degraded performance for the flexure mount can be caused by the mounting fixture and not the mount itself.
- When mounting optics into mounts, users should consider both alignment stability and minimized optical distortion. When comparing set-screw mounting options for optics, the nylon-tip set screw provides slightly lower wavefront distortion values but the oval-tip set screw provides more thermal stability. For optimal wavefront performance, the six-point mirror retainer gives significantly better results than a set-screw retainer.

Understanding the subtle performance characteristics of these components, from the optic to the table top, can make a big difference in the success of your overall application.



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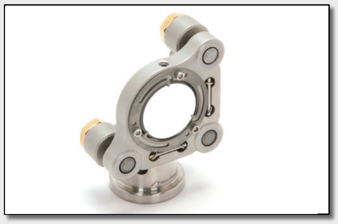

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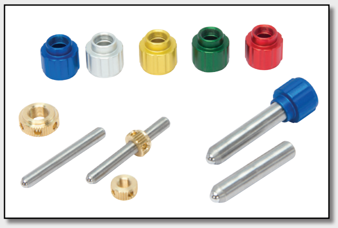

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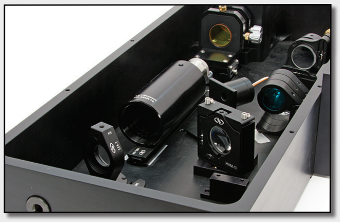

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