Positioning Performance and Accuracy

DEGREES OF FREEDOM IN POSITIONING DEVICES

A degree of freedom is defined as movement that is used to position an object in a specific direction of motion. In a three-dimensional space, there are six degrees of freedom. In the Cartesian coordinate system, there are three linear degrees of freedom (x, y, and z), which correspond to the coordinate axes, and three rotational degrees of freedom (θx, θy, and θz), which correspond to the rotation about each of the coordinate axes (see figure 7.1).

Optical component positioning tools are designed to offer the capability of adjustment in one or more specific degrees of freedom. For example, a one-axis opto-mechanical mount or positioning device is designed to provide only one direction of motion and constrain motion in all other axes. Vertical stages could be used for applications in which it is necessary to adjust the height of an optical component with respect to the surface plane of the optical table. For applications in which angular motion is necessary (e.g., adjusting the orientation of the optical axis), it would be necessary to use opto-mechanical component stages with a tilt adjustment capability. For applications requiring a purely angular adjustment, the suitable types of opto-mechanical positioning devices would be rotary mounts and stages or goniometers. Opto-mechanical components used for positioning are available with varying levels of complexity, ranging from single-axis devices with only one degree of freedom to multiaxis systems with up to six orthogonal degrees of freedom. It is also possible to stack several single-degree-of-freedom components to obtain motion capability along several axes; however, the degree of precision and stability provided by the stack of components will be inferior to that of each of its individual building blocks.

KEY ALIGNMENT PARAMETERS

Resolution

Resolution is the smallest increment of motion any particular positioner can provide. On a majority of positioners, motion is controlled by actuators, such as thumbscrews or micrometers, which convert rotational motion into linear motion. The ultimate resolution of motion is determined by the effective pitch of the threads on the actuator, the stiction of the device, and the ability of the operator to adjust the device repeatably. In general, thumbscrews with large-diameter knobs have greater resolution than those with small-diameter knobs, and the higher the thread density, the higher the resolution. In specifications, resolution is based on the ability of a reasonably knowledgeable and moderately skilled operator to make adjustments routinely, typically from one to five degrees of actuator rotation.

In the case of motorized positioning systems which perform the positioning function in an automated fashion, it is typically the mechanical configuration of the driver hardware that establishes the degree of resolution. In stepper-motor mechanisms the motion of the positioner can be made only in integer multiples of the predefined amount of resolution. For example, a stepper motor and stage combination with a resolution of 5 μm could move an object only to a location that is an integer multiple of 5 μm away from its starting reference point (e.g., a distance of 5, 10, 15, 20 μm . . .). In such a system, it would not be possible to move the object to a point 14 or 53 microns away from its current position.

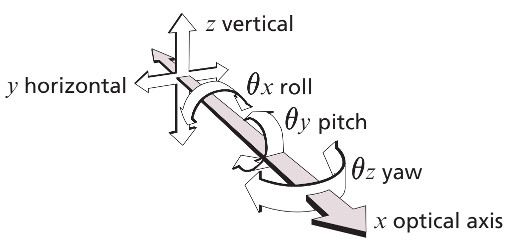


Figure 7.1 **Six degrees of freedom: x, y, z and θx, θy, θz**

Repeatability

Repeatability is the error within which a given position can be reproduced. Unidirectional repeatability, measured by approaching a position from a single direction, hides errors caused by backlash effects. Bidirectional repeatability, measured by approaching a position from opposing directions, includes these effects and provides a more meaningful specification.

Accuracy

Accuracy is the absolute deviation between desired and actual position. It is usually associated only with the axis or axes of intended travel of the opto-mechanical positioning tool.

Abbé Error

The linear positional error caused by the combination of the axes of measurement being offset from the plane of motion, as well as an angular error in that motion, is referred to as the Abbé error. The Abbé error has the worst impact on linear positioning accuracy. The Abbé error increases as the distance between stage bearings and the mounted component increases. This might occur, for example, with post-mounted components on a stage. An angular error in θy (pitch) of a stage will result in a positional error in y and an axis shift in z of a post-mounted component. Sources of Abbé error include way curvature, preload variation along a way, insufficient preload or backlash, contamination between the bearings and way surfaces, and torsional compliance caused by external forces acting on the load and overhanging components. The Abbé error can be minimized by keeping the axis of measurement as close to the plane of motion as possible. The Abbé error for a post-mounted component is illustrated in figure 7.2.

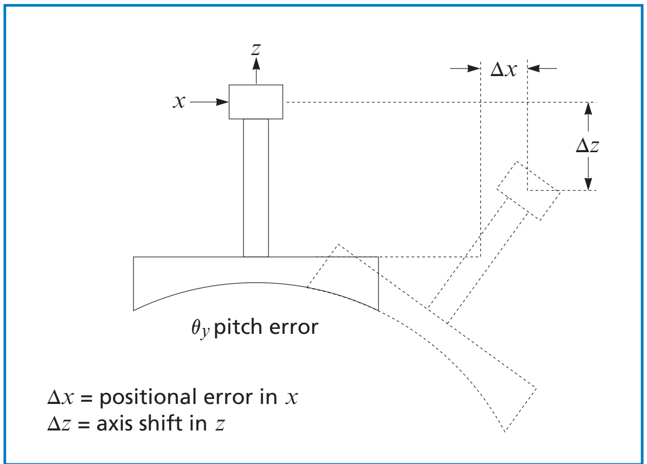


Figure 7.2 **Abbé error of a post-mounted component**

Cosine Error

Cosine error results from an angular misalignment between the motion of the translation stage and that of the actuator (or other accuracy-determining component). The magnitude of the error, equal to the actuator travel times (1-cosß) where ß is the actuator misalignment, has a negligible effect on the overall accuracy of the stage. For example, if a translation stage with 25 mm of travel has an actuator with a one-degree misalignment, this results in an error of just 3.8 µm over the entire range of travel.

Other Sources of Error

Other errors commonly associated with performance limitations of optical positioners include straightness of travel, angular deviation, wobble, and eccentricity.

When an opto-mechanical positioning component is moved along its intended direction of motion (for example, along the x-axis), it also tends to move along the y- and z-axes. The specification for this undesirable movement is called *straightness of travel* if the motion is horizontal (y) motion and *flatness* if the motion is vertical. In both cases it is defined as the maximum deviation that can occur in the undesired axis over the full length of travel in the intended axis (see figure 7.3).

Angular deviation is a measure of the unintended changes in the angle of the component platform of a linear stage as it travels over its full path length. Angular deviation can occur in any of the three angular degrees of freedom (θx, θy, θz).

In rotary opto-mechanical component mounts and positioning tools, in which angular adjustments are made to the object, two commonly encountered sources of error are *wobble* and *eccentricity*. These unintentionally induced movements occur along the angular and linear directions of motion. Wobble is a measure of the unintentional tilting of the axis about which the positioner is rotating. This in turn gives rise to a related error called eccentricity. A schematic representation of this concept is shown in figure 7.4.

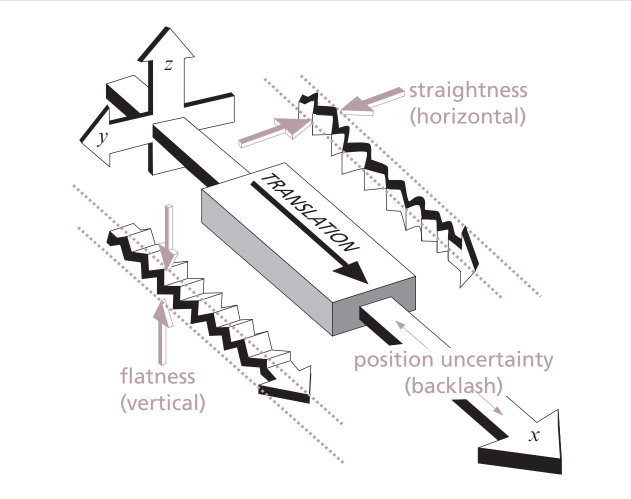


Figure 7.3 **Flatness and straightness of travel are sources of error in linear motion**

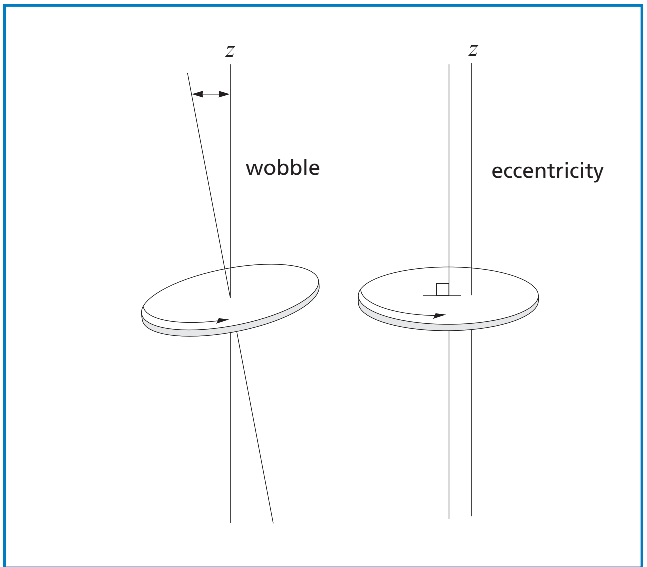


Figure 7.4 **Wobble and eccentricity associated with rotational motion**

COMMON ALIGNMENT SCENARIOS

Alignment is a term used to describe specific adjustment and optimization in experimental optics. Common optical alignment problems (see figure 7.5), which are encountered in an optical laboratory, include the alignment of an axis to a fixed point, the alignment of a point to a fixed axis, and the alignment of two axes, one to another.

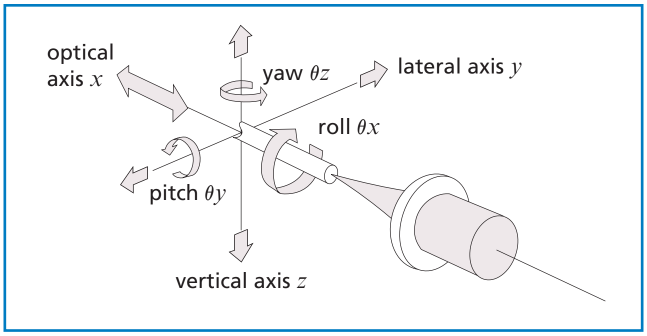
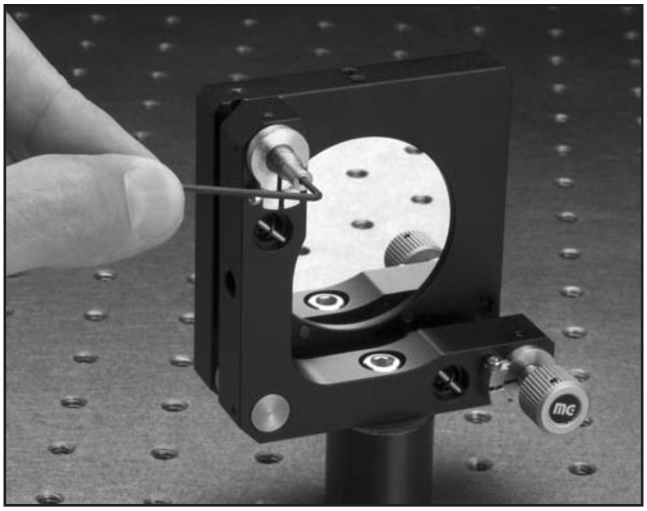


Figure 7.5 **A common alignment scenario**



High-resolution adjustments frequently require the use of a lever-arm tool such as an Allen wrench.

Aligning a Laser Beam to a Detector

This is a common example of aligning an axis (the beam) to a fixed point (the detector). In most cases, this requires either adjustment in two linear directions or adjustments in two angular directions. However, if the angular adjustment is about the axis of the linear translation (e.g., y and θy), it is possible to accomplish the alignment with a single linear and, single angular adjustment.

Aligning a Ball Lens to a Laser Beam

In the case of aligning a point (the ball lens) to an axis (the beam), linear adjustment is required in two orthogonal directions (x and y). If the beam is highly divergent, an adjustment in the z axis may also be required.

Aligning a Collimator to a Laser

In aligning two axes, the laser beam and the optical axis of the collimator, adjustments in two linear and two angular directions are required. Because any angular adjustment of an axis simultaneously produces a linear translation, this type of alignment procedure is the most demanding. To achieve proper alignment, one must first use angular adjustments to make the axes parallel and then use linear adjustments to make the axes collinear. Adding an additional adjustment capability parallel to the optical axis provides focusing capability as well as axial alignment capability.

More complex alignment problems require more degrees of freedom. In many cases a single type of positioner cannot fulfill all the requirements of a specific alignment application. For example, the focusing mechanism of a lens may require both a long travel range and high resolution in the same axis. Because high-resolution positioning mechanisms typically have a relatively short range of motion, two stages may be required, one for coarse adjustment over a relatively long travel range and for fine adjustment over a short distance.