Mechanical Stage Design

Materials

Each material used for mechanical components in motion control has its own unique set of advantages and disadvantages. The following is a summary of the properties for the most common materials used in motion mechanics.

Stiffness

Stiffness is a measure of the amount of force required to cause a given amount of deflection. Force and deflection are proportional and related by the equation:

$$\Delta x = (1/E) * xF/A$$

where F and Δx are force and deflection, respectively, x is the nominal length, and A is the surface area perpendicular to the force. E is a material-dependent constant called the modulus of elasticity, Young's modulus, or simply the stiffness of a material. Larger values of E mean greater material stiffness.

Thermal Expansion

Thermal expansion is the change in size or shape of an object, such as a stage, due to a change (increase or decrease) in temperature. The amount of change is dependent on the size of the component, the degree of temperature change, and the material used. The equation relating dimensional change to temperature change is:

$$\Delta L = \alpha L \Delta T$$

where α is the material-dependent coefficient of thermal expansion.

Thermal Conductivity

Some materials, such as aluminum, are good choices when temperature change across the component is non-uniform. This occurs when mounting a heat source, such as a laser diode. Because the diode is hotter than the surrounding environment, it dissipates heat through the mount, setting up a temperature gradient along the stage. If the material does not readily dissipate the heat, then distortions caused by thermal gradients can become significant.

The distortion caused by non-uniform temperature changes is proportional to the coefficient of thermal expansion, α, divided by the coefficient of thermal conductivity, c.

Relative thermal distortion = α/c

If the ambient operating temperature of the component is much different from the room temperature, then close attention should be paid to components made with more than one material. In a linear stage, for example, if the stage is aluminum while the bearings are stainless steel, the aluminum and steel will expand at different rates if the temperature changes, and the stage's bearings may lose preload or the stage may warp due to stresses built up at the aluminum–steel interface.

Material Instability

Material Instability is the change of physical dimension with time (also called cold flow or creep). For aluminum, brass and stainless steel, the period of time required to see this creep may be on the order of months or years.

Aluminum

Features

Aluminum is a lightweight material, resistant to cold flow or creep, with good stiffness-to-weight ratio. It has a relatively high coefficient of thermal expansion, but it also has a high thermal conductivity, making it a good choice in applications where there will be thermal gradients or where rapid adjustment to temperature changes is required. Aluminum is fast-machining, cost-effective, and widely used in stage structures. Aluminum does not rust, and corrosion is generally not a problem in a typical user's environment, even when the surface is unprotected. It has an excellent finish when anodized.

Limitations

Anodized surfaces are highly porous, making them unsuitable for use in high vacuum.

Coatings

Anodized aluminum provides excellent corrosion resistance and a good finish. Black is the color most often used. Anodizing hardens the surface, improving scratch and wear resistance. Aluminum may also be painted, with excellent results.

Steel

Features

Steel has a high modulus of elasticity, giving it very good stiffness (nearly three times that of aluminum) and good material stability. It also has about half the thermal expansion of aluminum (Figure 13), making it an excellent choice for stability in typical user environments where there are uniform changes in temperature. Stainless steel is well suited to high vacuum applications.

Limitations

Machining of steel is much slower than aluminum, making steel components considerably more expensive. Corrosion of steel is a serious problem, but stainless steel alloys minimize the corrosion problems of other steels.

Coatings

Steel parts are generally plated or painted. Platings are often chrome, nickel, rhodium, or cadmium. A black oxide finish is often used on screws and mounting hardware to prevent rust. Stainless steel alloys avoid the rust problems of other steels. They are very clean materials that do not require special surface protection. A glass-bead blasted surface will have a dull finish so that it does not spectacularly reflect.

Brass

Features

Brass is a heavy material, denser than steel, and fast machining. The main use of brass is for wear reduction; it is often used as a dissimilar metal to avoid self-welding effects with steel or stainless steel lead-screws or shafts. Brass is used in some high precision applications requiring extremely high resistance to creep and can be diamond turned for extremely smooth surfaces.

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Parameter	Steel	Aluminum	Brass	Granite
Young's Modulus (stiffness), E (Mpsi)	28	10.5	14	7
Density, ρ(lb/in³)	0.277	0.097	0.307	0.1
Specific Stiffness, E/ρ	101	108	45.6	70
Thermal Expansion, α(μin/in/°F)	5.6	12.4	11.4	4
Thermal Conduction, c (BTU/hr-ft-°F)	15.6	104	67	2
Relative Thermal Distortion, α/c	0.36	0.12	0.17	2

Figure 13 — Properties for Common Stage Materials.

Limitations

Compared to aluminum and steel, brass has a less desirable stiffness-to-weight ratio. Moreover, although the thermal expansion of brass is similar to that of aluminum, its thermal conductivity is nearly a factor of two worse.

Coatings

For optical use, brass is usually dyed black. In other cases, it may be plated with chrome or nickel for surface durability.

Granite

Features

Granite's unique physical characteristics, combined with new advances in machining methods, make granite structures one of the best choices for air-bearing support structures. The flatness of the surface is often a major factor in the positioning accuracy and repeatability of a total system.

The polished granite surfaces of these structures are among the flattest commercially available. Skilled hand-lapping procedures can produce geometric surfaces flat to 1.5 μm per square meter. Automated machine processes typically achieve 15 μm flatness per square meter.

An important characteristic of granite is its extreme hardness, which enables it to be lapped to very tight flatness specifications. Tests confirm that granite is more wear-resistant and shock-resistant than steel and granite's high strength makes it particularly suitable to large-scale systems with heavy static loads. Granite is also non-magnetic, making it excellent for electron beam applications, and most chemicals affect it.

The outstanding dimensional stability of granite also contributes to its usefulness in precision support structures. Granite is completely free of internal stresses which results in uniform, predictable response to thermal changes. Granite's high mass also gives it high thermal inertia, which protects experiments and processes from being affected by short-term ambient temperature fluctuations.

Limitations

For large structures and table surfaces, the mass of a granite structure can become large. For applications where extreme flatness is not important, steel honeycomb structures offer better weight-to-stiffness properties and can be damped for specific frequencies to optimize system performance.

Bearings

Bearings permit smooth low-friction rotary or linear movement between two surfaces. Bearings employ either a sliding or rolling action. In both cases, the bearing surfaces must be separated by a film of oil or other lubricant for proper performance.

The load and trajectory performance of a translation or rotation stage is primarily determined by the type of bearings used.

Dovetail Slides

Dovetail slides are the simplest types of linear stages and are primarily used for manual positioning. They consist of two flat surfaces sliding against each other with the geometry shown in Figure 14. Dovetail slides can provide long travel, and have relatively high stiffness and load capacity. They are more resistant to shock than other types of bearings and are fairly immune to contamination. However, they do have relatively high stiction, and their friction varies with translation speed, which makes precise control difficult and limits sensitivity.

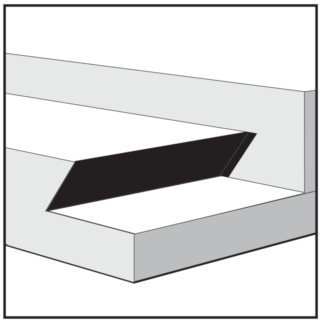

Figure 14—Dovetail slide

Ball Bearings

Ball bearing slides reduce friction by replacing sliding motion with rolling motion. Balls are captured in guideways by means of vee-ways or hardened steel rods (as shown in Figure 15). The guide ways are externally loaded against the balls to eliminate unwanted runout in the bearings. Even with this preload, the friction is very low resulting in extremely smooth travel. Ball bearing slides are relatively insensitive to contamination because each ball contacts the guideways at only a single point, allowing debris to be pushed out of the way.

With a vee-groove bearing way, ball bearings have a lower load capacity than crossed-roller bearings, since the contact area available to transmit loads is smaller - so in order to carry the same size load, the balls would need to have a larger diameter or be greater in quantity.

If the mating ways are ground with either an arch or circular groove (see Figure 16), the closer conformity to the balls' radii allows the use of smaller balls than with flat ways. The arch approximates a vee-shaped way with the load effectively split at angles of about 45 degrees with the vertical into two loads on the way.

A circular shaped way has a higher load capacity, but the balls bear the load on the bottom of the groove, which can result in side play for loads that are perpendicular to the direction of motion.

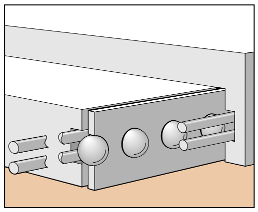

Figure 15—Ball bearing slides have extremely low friction with moderate load capacity.

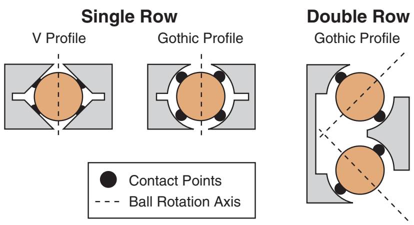

Figure 16—The type of bearing way, ball diameter, and number of balls affect the load capacity of a stage.

Crossed-Roller Bearings

Crossed-roller bearings (see Figure 17) offer all of the advantages of ball bearings with higher load capacity and higher stiffness. This is a consequence of replacing the point contact of a ball with the line contact of a roller. Due to the averaging characteristics of line contacts, angular and linear deviations are generally below those found in ball bearings. However, crossed-roller bearings require more care during manufacture and assembly, resulting in higher costs. Crossed-roller bearings are also more sensitive to contamination because they are less effective at pushing foreign particles away from contact with the guideways.

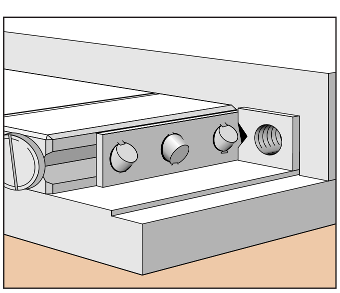

Figure 17—Crossed-roller bearings have all the advantages of ball bearings with greater stiffness and load capacity.

Recirculating Bearings

Recirculating bearings use balls or rollers that recirculate in a track mounted to the carriage. These modules travel along a precision ground rail on each side of the stage base track and rails (see Figure 18). Recirculating bearings are typically not as smooth as linear bearings, since the balls or rollers must enter and exit the preload region; but they allow for very long travel ranges and provide a higher load capacity for applications with off-center axial loads. In addition, due to their design, there is no bearing cage migration, which can sometimes become an issue with linear bearing stages used for high duty cycle applications.

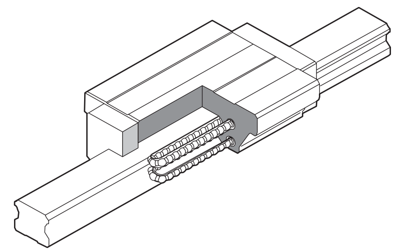

Figure 18—Recirculating bearing allows very long travel range and high load capacity.

Drive Systems

Common drive systems for linear and rotary precision positioning mechanics include the lead screw, ball screw and worm drive. Shaft couplings and gearboxes, which affect system dynamics such as speed, load capacity, backlash, and drive stiffness are located between the drive system and the motor driving it. Gearboxes are most often integrated with the motor.

Lead Screw

A very popular technique for moving loads is to use the axial translation of a nut riding along a rotating screw (see Figure 19). Lead screws use sliding contact, so their wear rate is directly proportional to usage. The advantages of lead screws include self-locking capability, low initial costs, ease of manufacture, and a wide choice of materials.

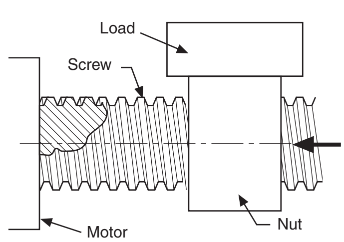

Figure 19—As the lead screw rotates, the load is translated in the axial direction of the screw.

Recirculating Ball Screw

Recirculating ball screws are essentially lead screws with a train of ball bearings riding between the screw and the nut in a recirculating track (see Figure 20). The large number of mating parts make tolerances critical and thus raise manufacturing costs. The screw profile has a rounded shape to conform to the recirculating balls. The primary advantage of ball screws over lead screws is higher efficiency, or the amount of energy output for energy input. However, because they are not self-locking, ball screw driven stages require an auxiliary brake to prevent back driving. Additional advantages of ball screws are predictable service life and lower wear rate.

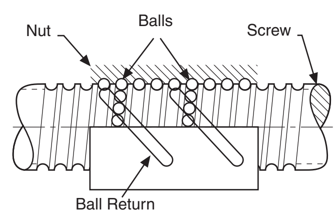

Figure 20—Ball screws use recirculating balls to reduce friction and gain higher efficiency than conventional lead screws.

Worm Drive

The worm gear system is a method of transforming rotary motion in one direction into rotary motion in another direction by meshing a screw (worm) with a gear (worm wheel). As the screw is turned, the worm threads meshing with the gear causes it to rotate (see Figure 21). Advantages of worm drives over direct drives include higher velocity ratios and higher load capacities.

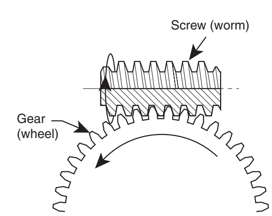

Figure 21—Worm drive systems can provide high speed and high torque.

Gearboxes

Gearboxes are used to transmit rotational motion and power. They are frequently used in reduction to produce increased resolution and torque that may be difficult or impossible to produce with standard motors. A 10:1 gearbox, for example, produces one turn of its output shaft for every 10 turns of its input shaft. A 200-step motor with this gear combination would be viewed as a device with an effective resolution of 2000 points per revolution of the output shaft.

In addition to changing resolution, gearboxes with non-unity gear ratios also change the available output torque and speed. In the example above, the torque is increased and the speed is decreased.

Flexible Shaft Couplings

Couplings are used in a drivetrain to transmit power and motion between two independent shafts that may not be perfectly aligned (see Figure 22).

Flexible couplings generally allow for some parallel and angular misalignment. Depending on their design, they may accommodate more misalignment, have higher torsional stiffness and load capacity, or be capable of higher speeds (see Figure 23).

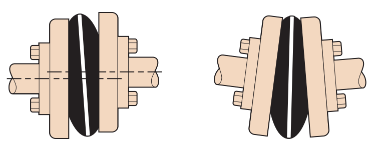

Figure 22—Shaft couplings adjust for and accommodate angular and parallel misalignment between rotating shafts.

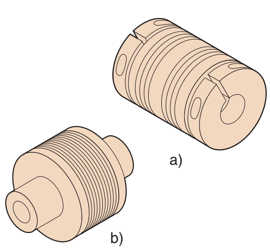

Figure 23—Flexible couplings are made from many designs.
a) Helical. No backlash and constant velocity under misalignment. Adaptable to high speed applications.
b) Bellows. Generally for light-duty applications. Misalignments to 9° angular, 1/4 in. parallel. Good to 10,000 rpm.

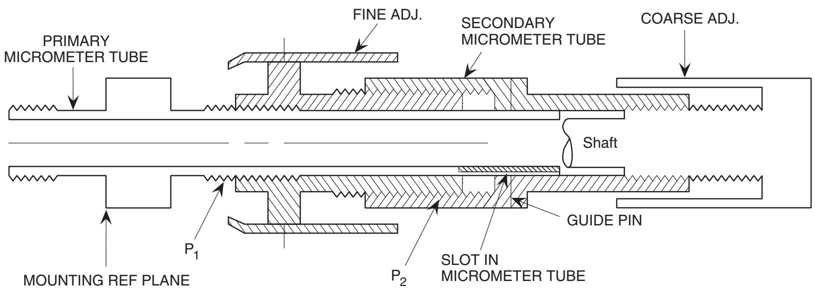

Figure 24—Construction of a differential micrometer. Two threads of nearly the same pitch (P1, P2) are used to yield very fine motion.

Drive Options

Manual Drives and Actuators

Manual actuators are the simplest and lowest cost options for positioning. A manual actuator can be described as a high sensitivity lead screw with a knurled knob. On many manual linear stages, like our 460 or 423 series, the nut of the screw is fixed to the stage body, and the screw itself moves back and forth (in contrast to lead screw driven systems, where the nut moves back and forth). Springs press the carriage against the screw tip to make good contact and to preload the screw to eliminate backlash.

Fine Adjustment Screws

High resolution, ultra-fine adjustment screws, found in Newport's AJS Series, use rolled threads for smooth actuation and have a ball tip to reduce wear and minimize undesirable lateral motion. Featuring a pitch between 80 and 127 threads per inch (TPI), these screws permit sub-micron adjustments. When no position readout is required, fine adjustment screws are not only a lower cost option, but they also offer superior sensitivity compared to metric micrometer screws, which have 50 threads per 25 mm. Examples where position readout is unnecessary can be found when position may be monitored from the orientation or position of a laser beam or from the amount of optical power coupled through a system.

Micrometer Screws

Micrometer screws are used if accurate position read-out, like repeatable positioning, is needed. Standard metric micrometer screws feature 50 threads per 25 mm and have a scale in units of 10 µm. An additional vernier - available on some versions - allows position readings with a resolution of 1 µm.

Differential Screws

When resolution of much less than one micron is needed, a differential screw is recommended. These devices use the difference between two screws of nearly the same pitch to produce very fine motion. The motion achieved equals the difference between the two screw pitches. This is illustrated in Figure 24.
The effective pitch is given by
$1/P_{eff} = 1/P_1 - 1/P_2$

For example, in the patented DM-13 differential micrometer screw offered by Newport, the two screw pitches used have 20 threads per cm for the standard coarse adjustment micrometer barrel and 21.05 threads per cm (200 threads per 9.5 cm) for the differential barrel. The resultant effective pitch is equivalent to 400 threads per cm. This micrometer has a sensitivity of 0.07 µm.

DC Brush Motors

A brushed DC motor essentially consists of a rotor placed in a magnetic field, which causes rotation when current is applied to the motor windings. The rotational speed is proportional to the applied voltage, while the torque is proportional to the current. DC motors are best characterized by their smooth motion and high speeds. A dynamic range of 10^3 to 10^4 is commonplace. DC motors also provide good efficiency and a high power/weight ratio. Unlike stepper motors, DC servo motors do not provide full torque when idle.

Precise closed-loop servo positioning and speed control is typically achieved with a shaft-mounted rotary encoder. However, applications requiring ultra-precise positioning may incorporate a high-resolution direct reading encoder on the drivetrain along with a shaft-mounted tachometer.

Stepper Motors

A stepper motor operates using the basic principle of magnetic attraction and repulsion. Steppers convert digital pulses into mechanical shaft rotation. The amount of rotation is directly proportional to the number of input pulses generated, and speed is relative to pulse frequency. A typical stepper motor has a permanent magnet and/or an iron rotor with a stator. Commutating the motor, as illustrated in Figure 25, generates the torque required to turn the stepper motor.

One difference between a DC and a stepper motor is that when a voltage is applied to a DC servo motor, it will develop both torque and rotation. However, when a voltage is applied to a stepper motor, it will develop only torque. For the motor to rotate, the current applied must be commutated or switched.

Commutation is the principle by which the amplitude and direction of the current flowing in the electro-magnetic coils within the motor changes. A brushed DC motor is designed to self-commutate while a stepper motor lacks internal commutation.

By applying current to the electro-magnetic windings, stepping motors are able to move in a continuous point-to-point positioning manner. When at rest, a full-step motor's stop position does not drift because there is an inherent holding or detent torque without power applied. For this reason, steppers at rest generate little heat, making them suitable for position-and-hold vacuum applications where heat dissipation is more difficult.

By energizing two windings simultaneously, it is possible to electronically divide a full-step motion into ten or more partial steps. This method is called mini-stepping or micro-stepping and can improve the smoothness of motion and resolution of a positioning system.

Stepper motors are often used open-loop to provide a low-cost alternative to closed-loop DC servo systems. The count of pulses is a good indicator of position but can be unpredictable with a large number of micro-steps, high loads, or high accelerations. Skipped or extra steps and misperformed micro-steps are frequent problems in open-loop configurations for high performance systems. For this reason, Newport uses most of its stepper motor products in closed-loop operation.

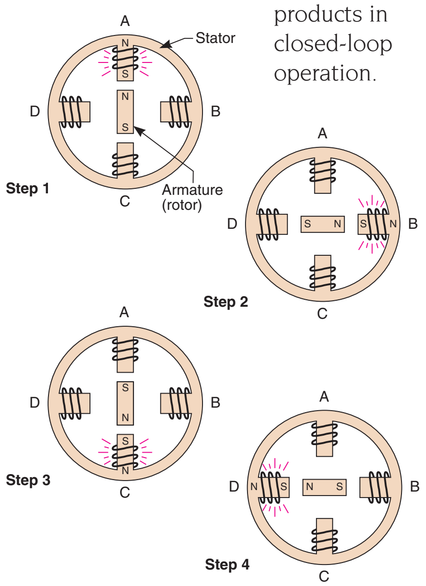

Figure 25—Rotation in a stepper motor is generated by alternately energizing and de-energizing the poles in the motor's stator, creating torque which turns the rotor.

Vacuum Compatibility

Stages used in a vacuum of 10^{-6} torr or better must be specially prepared for that environment. Many of the materials used in standard linear stages will outgas in high vacuum, resulting in a "virtual" leak, which limits the ability to maintain adequate vacuum.

Procedures used at Newport to specially prepare products for use in vacuum environments ensure that our products will function as designed at pressure levels down to 10^{-6} torr and at the same time not release unacceptable quantities of contaminants into the vacuum environment. For proper preparation, more information in addition to operating pressure is needed. Acceptable levels of outgassing, mass loss, and volatile condensable materials can vary with the application, pumping capacity, temperature, etc.

Material issues that must be addressed include the selection of acceptable metals, ceramics, coatings, lubricants, adhesives, rubbers, plastics, and electrical components, etc. For example, highly porous anodized aluminum surfaces trap large amounts of air molecules, resulting in significant outgassing. For this reason, aluminum used in high-vacuum applications is unanodized. Motors must also be specially prepared for vacuum operation.

Machining practices must avoid creating surfaces conducive to trapping gases and other foreign materials that could be released in vacuum conditions. Care must also be taken to ensure that gasses are not trapped in assembly cavities.

In addition to material selection and manufacturing practices, special cleaning, handling, assembly and packaging practices must be followed. These functions are carried out in a clean environment to minimize the possibility of airborne contaminants becoming attached to the components. Newport does not perform bakeout at an elevated temperature.

Performance specifications for products used in a vacuum environment may vary from non-vacuum use. For example, because heat cannot be as readily dissipated, motor duty cycle must be reduced, which in turn may limit the maximum achievable speed. If your application requires vacuum preparation, please contact our Applications Engineering Department to discuss your specific application needs.

Cleanroom Compatibility

Newport has facilities to properly prepare products for cleanroom applications. While many of the techniques, practices, procedures and material requirements for cleanroom applications are similar to those for vacuum preparation, each application has its own unique requirements. Please contact our Applications Engineering Department to discuss your specific application needs.