# Precision Motion Control In Vacuum Environments

Introduction

Precision motion control applications in a vacuum environment requires careful consideration to stage configuration, material selection, operating temperatures, and position feedback. As a vacuum chamber creates a negative atmosphere, the effects of outgassing and the elimination of air flow effects the ability to position accurately. There are many design considerations that range from stage configuration and cable management to the use of lubricants that must be thoroughly evaluated and factored into the design of a motion system. Moreover, as vacuum levels vary drastically, from a medium vacuum ($10^{-3}$ Torr) to an ultrahigh vacuum ($10^{-10}$), the material selection and stage configurations vary as well.

Stage Configurations

When designing a motion system for use in a vacuum chamber, consideration must be given to:

- Material Selection
- Cleanliness & Handling
- Drive & Bearing Selection
- Position Feedback
- Heat generation: Compatibility and proximity to feedback devices or other temperature sensitive element
- Use of lubricants (wet vs dry)

In general terms, each of the considerations above raise issues not just from the vacuum perspective, but fron the motion perspective. For example, while recirculating linear guides have become a well accepted technology in precision motion control systems, it is very difficult to apply these bearings in temperature varying environments. Additionally as these types of bearings use a ball compression preload with a high contact surface, the drag force and resulting friction creates demands for specific lubricants and can potentially be a heat generator, in and of itself. In many instances a non-recirculating low friction bearing is more appropriate. As well, these options and issues apply to the various drive mechanisms and can have similar effects on encoders. Heat on the other hand, creates a different set of problems as it effects positionin and bearing preload both a result of coefficients of thermal expansion.

Inherent in the material selection are the compatibility issues with a vacuum environment. Specific materials are acceptable at various levels of vacuum and certain applications have restrictions related to process. As well, the thermal issues and stage configurations create limitations on the what materials can be used and the resulting structural stiffness, effecting the ultimate servo performance.

While precision motion control is not a new subject, the proper design of precision motion systems, well suited to vacuum environments remains a challenge. There are many areas of consideration, ranging from design and operating temperatures to the cleanliness of how a product is handled and packaged. While this paper has focused on the component selection with respect to operating in a vacuum environment, general design practices must be considered as well. In designing precision motion systems for vacuum, the elimination of voids and blind holes must be taken into account. The use of vented hardware and holes, as well as eliminating closed pockets is necessary for all structures in vacuum, not just precision motion systems.

The purpose of this paper is to explore the issues surrounding precision motion in vacuum and identify the design considerations and component selection to successfully position accurately in vacuum.

**Material Selection**
Early on in the design process consideration must be given to the proper selection of materials. This process must give consideration on two discrete levels; one simply being the use of vacuum compatible materials, an the second being any particular materials that limit the user's process.

While each vacuum application may vary, with respect to allowable materials that are used in vacuum, there are some basic guidelines, regardless of vacuum level, that should be followed with the construction of motion systems. Most motion systems today utilize a steel or stainless steel bearing construction. Stage housings are typically aluminum or cast iron, and the drive mechanisms are almost always steel or stainless steel. General guidelines are:

Aluminum
Aluminum is used quite extensively in vacuum environments. Plate and extrusion are well accepted up to ultra high vacuum levels, however cast aluminum or cast jig plate would not be appropriate, due to porosity (trapped air) found in cast aluminum. Standard grades of aluminum in the 6000 and 7000 series are most common for motion system construction, with typical alloys of 6061-T6 or 7075-T6.

Steel
Most bearing and drive structures use tool steel and bearing steel alloys, such as 52100 Bearing Steel or A2, A6, and O2 Tool Steels. While these materials can be cleaned and well prepared for vacuum, they are corrosive materials and they possess magnetic properties. In applications that require the elimination of magnetic fields, these materials are typically not appropriate.

Stainless Steel
While stainless steels are preferred over most steels, there may be issues with weight or hardness, as it relates to its role in motion control. Most bearing structures are available in 400 series (440C) stainless steels, which can provide good hardness. However, this material is still slightly corrosive and has magnetic properties. Particularly in the manufacture process of bearing races, there are several grinding methods that rely on the magnetic properties to hold the material, making 400 series much more suitable than 300 series, which is completely nonmagnetic. While 300 series is often a preferred alloy, there are manufacturing and hardness obstacles which may make it less appropriate for use in motion systems.

Copper & Nickel
Copper will outgas at rates similar to stainless steel and may be well suited to vacuum environments. Copper however is typically avoided if the motion system goes through a bake out process. Similarly with Nickel, while it is considered vacuum compatible, it is usually avoided, in a motion system, if there is a bake out process.

Other Metals
While Titanium is vacuum compatible, it is not often found on motion systems. Titanium does however provide the ability for a motion system to maintain the same thermal coefficients of the bearings and the housings, keeping uniform bearing stiffness throughout any temperature change. The difficulty in machining and cost make this a rare material in motion control systems.

Nonmetalic Materials

The only nonmetalic materials used in vacuum are Teflon or Viton. Both of these materials are vacuum compatible up through an Ultra High Vacuum. It should be noted that in lower vacuum levels ($10^{-6}$ and below), it is common to find materials such as Nylon or Phenolic being used in vacuum. While usually considered non-compatible materials, some processes use these materials, accepting the outgassing levels they generate.

Ceramics

Ceramics, such as Alumina, are well suited to vacuum, as they are thermally stable and very clean. Again, though, there are few ceramic materials used in motion control systems. However, we will explore the use of ceramics as a rolling element bearing (ball bearing) and its use as an integral part of a piezo motor, for driving motion systems.

Generally, while there are a variety of materials that are considered "Vacuum Compatible", there is a typical subset of these that are used in precision motion control solutions. Housings are typically of aluminum (unanodized), while bearing structures are of steel or 400 series stainless steel. Motor technology can be rotary motor, linear motor or piezo motor, each with its own set of properties.

**Cleanliness and Handling**

Contamination can be one of the most troubling issues as it relates to motion performance and the users process. The utmost in care must be given to cleaning all the materials, and how they are handled once cleaned. As grease and oil will not only outgas, but can potentially contaminate the chamber. All parts should be properly degreased. There are four fundamental steps that should be followed for proper chemical cleaning of vacuum materials. These steps may vary based on individual requirements and regulations:

General: To remove debris, soiling, Surface coatings
Degreasing: To dissolve oil, grease
Etching/Pickling: To remove bonded and buried contaminants. The etching will remove a thin surface layer with mild acid or alkaline oxide layers. The pickling will remove the oxide layer and underlining metal which will reduce corrosion resistance provided by the oxide layer and produce a non-uniform finish. The material should be passivated to rebuild oxide layer.
Rinse: To remove cleaning agents

General (non-chemical) cleaning can be achieved through brushing or wiping however where possible the tools should be harder than the material being cleaned, to avoid deposits. No abrasive particles, such as grinding wheels, should be used. Glass bead or alumina power blasting (or electropolishing) can be used to remove paints or markings, but a water rinse should be used afterward to wash away loose material. These cleaning processes are designed to smooth out the surface and lower outgassing rates.

Common Solvents for Vapor/Bath Degreasing

| Solvent | Boiling Point Deg C |
|---|---|
| Trichloroethance | 72 |
| Trichloro-trifluoroenthane Freon 112 | 56 |
| Perchloroethylene | 121 |
| Trichloroethylene | 40 |

As it relates to motion control systems, there are specific methods to clean aluminum and stainless steels. These steps should be followed for materials uses in the construction of precision stages.

Basic Cleaning of Aluminum

Hot (65 deg C) trichloroethane bath with ultrasonic agitation or perchloroethylene vapor (121 deg C) degreasing.
Hot (60 deg C) non-etch alkaline detergent (pH~10) rinse for 20 minutes with alconox, alutone, or equivalent detergent.
Rinse in cold tap water, rinse in DI water
Immerse in 45C NaOH solution (caustic etch)
Rinse in tap water, rinse in DI water
Passivation in 2% $HNO_3$ solution
Rinse in DI water

Basic Cleaning of Stainless Steel

Hot (65 deg C) trichloroethane bath with ultrasonic agitation or perchloroethylene vabor (121 deg C) degreasing.
Hot (60 deg C) non-etch alkaline detergent (pH~10) rinse for 20 minutes with alconox, alutone, or equivalent detergent.
Rinse in cold tap water, rinse in DI water
Pickling in $HNO_3$ (33%), HF (33%) solution
Passivation with 2% $HNO_3$: for protective oxide layer
Rinse in tap water, rinse in DI water

Once cleaning processes are complete, parts should not come in contact with human hands or other materials that can potentially cause contamination. All parts should be handled with clean latex gloves (without any powders) and should be wrapped in clean material (aluminum foil or plastic). Caution should be used, as paper wrapping material or some plastics may contain oils that will contaminate the material after cleaning.

In addition to the cleaning of parts, all tools that come in contact with parts, during the building of a motion system should be appropriately cleaned. As well, work areas should be properly prepared and all staff working on motion system parts should be fully trained.

**Drive and Bearing Selection**

Both drive (leadscrew, ballscrew, or linear motor) and bearing selection relate not only to the performance that is required of the motion system, but also to the operating environment. All aspects of a motion systems mechanical construction must be carefully considered for material and operational properties, to understand how well they will function.

There are 3 common drive types used in precision motion control systems; leadscrews, ballscrews, and linear motors. While they all have different operating characteristics, all can be made vacuum compatible.

Leadscrews

Most precision leadscrews are made of tool steel (or 400 series stainless steel), and configured as a 60 degree V thread. The mated nut however, is often made of bronze, and not considered vacuum compatible. When using leadscrews in vacuum, it is common to simply convert the leadscrew nut material to a vacuum compatible steel or stainless steel.

Leadscrews are a friction device, with a sliding action between the thread and the nut. This action requires lubrication and will generate heat. Additionally, to improve the positioning performance of a leadscrew, the nut is typically preloaded. This is accomplished with either a pair of radial springs or the use of two nuts with axial springs. Adding springs to the operation of the leadscrew adds a new material, the spring, and limits the stiffness of the drive to the value of the spring force.

The most important consideration when using a leadscrew in a vacuum environment is the ability to provide appropriate lubrication to minimize the wear and reduce the heat from the friction action between the thread and the nut. While there are several 'wet' lubricants and a couple of dry lubricants that are vacuum compatible, most dry lubrication is not well suited to frictional conditions, and serve rolling elements better. Therefore it is more appropriate to use a vacuum compatible grease when using a leadscrew.

Ballscrews

Unlike leadscrews, ballscrews operate with very low friction, incorporating many recirculating ball bearings rolling between the thread and the nut. In this instance, the common constructions consist of tool steel, bearing steel, or stainless steel, all vacuum compatible materials.

Ballscrew preloads utilize the compression rate of the ball bearing itself, eliminating the need for springs or added elements. This makes the construction much simpler for use in vacuum. As well, being of a rolling element construction, the ballscrew is much better suited to using a permanent dry lubrication, described further in the lubrication section.

Lower operating torques and less stiction (starting friction) benefits vacuum operation, in that there will be less heat generation at the motor, however the operating characteristics between leadscrew and ballscrew should be considered relative to the process as well. Leadscrews are very smooth and can be used for scanning and slow speed operation. Ballscrews transmit vibration as balls circulate in and out of preload, and are not suitable for constant speed applications or ultra fine positioning. While both parts can be made vacuum compatible, consideration must be given from a holistic perspective, understanding performance and environment.

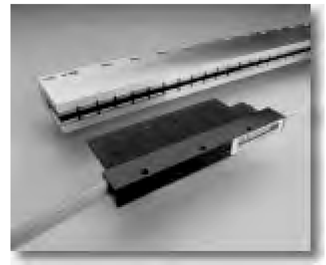
When applying either a leadscrew or ballscrew, consideration must be given to the rotary motor technology used. Both step and servo motors can be made vacuum compatible, but yield different operating conditions. A step motor can easily run open loop, but will tend to generate more heat. A servo motor requires position feedback, but will often not create as much of a heat issue.

Linear Motors

One of the most common drive technologies in precision motion control is linear motors. Typically in a configuration of Brushless DC, these motors are configured as a coil and bed of permanent magnets. Most Brushless dc motors are not produced in vacuum compatible configurations, however they can be.

The primary advantage of using a brushless dc linear motor in a vacuum environment is that there are only two pieces with absolutely no contact between them. There is no need to lubricate the motor and the heating issue is something that can be managed in the sizing process.

Ironless motors consisting of a motor coil encapsulated in epoxy, moving between two rows of opposing permanent magnets can be made vacuum compatible up to $10^{-8}$ level.



To provide this in a vacuum compatible configuration, the coil must be made with a vacuum compatible epoxy and potted in a vacuum, to assure that all trapped air is removed.

The magnets must be adhered with a vacuum compatible epoxy and coated with a vacuum compatible material. These types of linear motors, however, introduce a permanent magnetic field that must be considered within the scope of the user's process.

A newer and alternative drive technology for use in vacuum is a Piezo Motor. Shown below, the piezo motor consists of a machined aluminum housing with a series of pzt elements and ceramic (alumina) fingertips. These fingertips generate a walking action against another piece of ceramic, mounted to the moving portion. The advantage of the motor technology is the simplicity of materials, overall size, and the elimination of all magnetic fields.

The motor shown, mounts in a very compact configuration along side the motion system (axis). The motor operates as a friction drive, generating oscillations at the fingertip and causing the walking action.

While the operational characteristics often yields excellent performance benefits, caution should be given to potential heating issues. As a friction drive, the motor temperature will rise above ambient, regardless of the load applied. As the motor is off to the side, this may not be an issue, however in some cases it may be necessary to use a conducting metal wire to draw heat away from the motion system.

While the drive selection is critical to the indented performance of the motion system, it is also necessary to consider the implications as it relates to heat and lubrication, in vacuum applications. Leadscrews can be cumbersome to use as they require wet lubricant and will generate heat from its friction characteristics. Ballscrews, on the other hand, provide better operating characteristics, provided the lack of smoothness does not interfere with the positioning requirements. Any form  of a linear motor is more suitable, provided it is vacuum compatible.

(Linear) Bearings have similar issues as the drives, however there are a few more options. There are bearings that operate on a friction basis, which are typically not used in precision motion at all. Then, there are two types of anti-friction bearings; non-recirculating and recirculating, both of which can be made vacuum compatible, but with significantly different performance characteristics and costs.

Non-Recirculating Linear Bearings

Linear bearings such as crossed roller, needle bearing, or linear ball all operate under the principles of very low friction and very high accuracy. These bearings, in a non-recirculating configuration, generate a rolling action with all rolling elements under uniform preload, all the time. As the bearings and race can be configured in tool steel or stainless steel, and the operating coefficient of friction is ~.003, this bearings are ideal for operation in a vacuum environment.

Crossed rollers, in particular, provide the lowest operating coefficient of friction, often .001, eliminating any heat generation. This coupled with exceptionally high accuracy, smoothness, and stiffness, makes it a common selection for precision motion systems, in or out of vacuum environments.

Photo of crossed rollers

Crossed roller ways can be produced easily in steel or stainless and can incorporate stainless rollers or ceramic balls. In a non-recirculating environment, the bearings are preloaded mechanically, to generate a pure rolling action, creating a good balance between stiffness and friction and allowing slower operation with little or no lubrication or the use permanent dry lubrication.

Recirculating Linear Guide Bearings

Most recirculating linear guide bearings consist of a long rail with a short puck. A series of balls recirculate i the puck, providing the opportunity for very long travel, however much of the puck configuration uses plasti for the ball recirculation and rubber for the seals, both of which are difficult to make vacuum compatible.

The operation of a linear recirculating guide is dependent on removing all bearing clearance with a ball compression preload. This preload is achieved with an 'oversizing' of the ball bearings. As these balls are compressed to generate more than a tangential point contact, frictional drag is created. The stiffer the bearing preload the higher the drag. Because of this, lubrication is a necessity, and while the rolling element technology is compatible with a permanent dry lubrication, the dry lubrication alone will increase the resistance force.

Consideration must be given to the operating characteristics from a perspective of heat, vibration (as the balls recirculation) and driving torque or force requirements reflected back to the motor, creating additional heat issues.

**Position Feedback**

In precision motion applications, position feedback is typically accomplished with linear or rotary encoders mounted directly to the positioning system. There are only a few manufacturers who provide vacuum compatible encoders that are suitable for use and there is only one or two that provide products for use in ultra high vacuum.

Consideration must be given to the encoder technology and how it will react to heat and outgassing. As all encoders have wires attached to the read head, wire casings should be made of Teflon and proper shielding/grounding must be provided.

As the selection of available products are few, it is most important to consider the location of the feedback device on the motion system, to eliminate all effects from temperature and any other operating conditions.

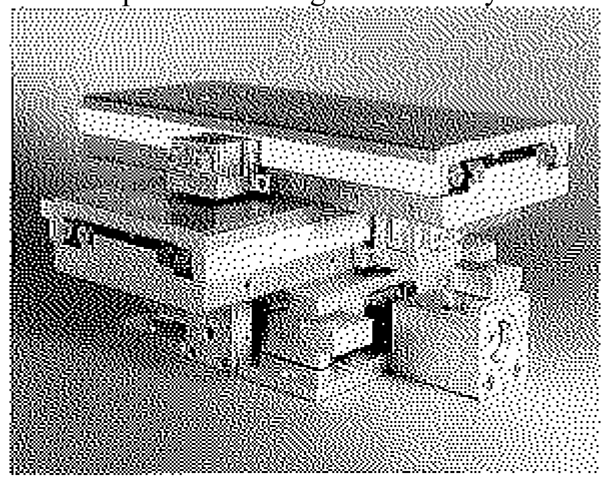
<u>The Motion System</u>

In defining a motion system, all aspects of the stage's mechanical construction and material selection are critical. While most stages utilize a low friction ball or roller bearing configuration for vacuum, the bearing structure should be based primarily on the specific motion requirements.

The typical drive is either a precision ballscrew or piezo motor, both of which can operate in vacuum with little, if any, side effects.

Shown here is a precision system for ultra high vacuum, using stainless crossed rollers with permanent dry lubricant and piezo motors in the X/Y axes. The base axis has a ballscrew and rotary motor drive.

Example of Ultra High Vacuum System



**Heat Generation**

Operating motors and precision motion systems in a vacuum creates new challenges with respect to heat generation. As a vacuum environment provides no opportunity for air cooling, there needs to be careful evaluation as to the source of the heat and what it may potentially impact.

Naturally the primary consideration, in managing heat, is how will it effect the motion performance, in terms of accuracy and repeatability, and will it effect the user's process. In terms of accuracy/repeatability, it is important to determine the heat path that will be created by the source, as conduction is the only manner in which heat will travel. Should heat generation migrate to a position feedback device, such as an encoder, then there will position errors that have to be considered.

In a precision motion system, the primary heat generator is the motor. Rotary motors are often mounted at one end of a system, and mounted to an aluminum bracket, coupled to the steel drive screw. Depending on the material of the vacuum chamber, the heat path may travel to the motion system, but never pass through the linear bearings or ballscrew, which is connected to the moveable portion. As well, the piezo motor that mounts to the base of a motion system is only connected to the moving portion via fingertip contact to a strip of ceramic. Again well isolated from the moving portion.

However, if the heat is near the feedback device, and the temperature of the entire chamber rises, accuracy impacts at the level of the materials' thermal expansion rates must be considered. As the temperature of a vacuum chamber rises, thermal expansion will undoubtedly effect the bearing preload, if any part of the housing is constructed in aluminum.

To successfully limit the effects of heat on a precision motion system, steps should be taken to move the heat away from the motion system. This can be accomplished in one of two manners. One method would be to provide cooling tubes that enter the chamber, circulate around the motor, and exit the chamber. This method can be quite effective if the motor is stationary, however, a moving motor would make this quite difficult. A second method would be to use a wire (mesh) that can circulate the motor and attach to the side of the chamber, away from the motion system. In a similar fashion to an umbilical cord, a loose wire, with the ability to move can effective conduct heat away from a precision motion system.

The alternative to mitigating the effects of heat sources would be to construct a system with materials that have a similar coefficient of thermal expansion. Producing a precision motion system in stainless steel or cas iron will allow all the materials, drive, housing, and feedback substrate to expand/contract at the same rates. While this may be allowable from an error tolerance, this direction does introduce a potential issue of large moving masses, which may create a drive problem.

## Lubrication

The concept of anti-friction bearings and low friction ball screws is quite appealing to vacuum environments as the lubrication requirements are minimal. Many times it is acceptable to utilize a permanent dry lubricant that can be applied to bearings or screw that is vacuum compatible and eliminate the need for future maintenance.

A permanent dry lubricant, of Tungsten Disulfied, provides a bond to the material it is applied to. The lubricant is .5 micron in molecular size and does not bond to itself. It is well suited to rolling element action, and can be supplemented with the use of (vacuum compatible) grease.

**Dry Lubricant Specification**

| | |
|---|---|
| Composition | Modified (WS2) Tungsten Disulfied in lamellar form |
| Hardness | 1.0 to 1.5 Moh's scale |
| Molecular Weight | 248.02 |
| Density | 7.4 gms/cc |
| Thickness | .0005mm or less |
| Appearance | Silver grey, rhodium when burnished |
| Co-efficient of Friction | .03 |
| Carrier | dry air, no binders or adhesives |
| Adhesion | mechanical molecular interlock |
| Cure time | no cure time required, applied at ambient temperature |
| Temperature Range | lubricates from -188 deg C to 538 deg C in normal atmosphere |
| Chemical Stability | inert, non-toxic, corrosion resistant |
| Corrosion Resistance | minor decay of corrosion, wil minimize corrosion of substrate |
| Magnetism | non-magnetic |
| Vacuum Environment | -188 deg C to 1316 deg C temperatures of $10^{-14}$ Torr |
| Substrates | all solid metals, glass, fiberglass |
| As a Substrate | accepts most paints, compatible with solvents and oils |
| Load Capacity | same as substrate to 350,000 psi |
| Lox Compatibility | insensitive to detonation by or in the presence of oxygen |
| Degradation | will not cause distortive stress relief, additional stresses or degradation to any surface |

Alternative to the dry lubricant, there are a host of low outgassing lubricants available on the market. It should be noted, however that the viscosity of vacuum compatible grease is typically high and will add resistance force to bearings and drive screws. As well, each grease has different operating temperature capabilities, which can effect the system if a bake out process is used.

In a rolling element drive or bearing, it is best if dry lubrication can be utilized. In applications that use precision crossed rollers with low duty cycles, there are opportunities to completely eliminate the use of lubricant, as the friction and wear are not an issue.

**Summary**

In addition to the selection of stage materials and configurations, it is important that good basic practice be used on designing, manufacturing, and testing of precision motion systems for use in vacuum. Efforts should be made, in the system design, to eliminate trapped air and outgassing, that would cause the pump to work harder than normal.

The selection of components must be compatible with the desired performance characteristics as well as the users process. While consideration must be given to general precision, heat, magnetism, material incompatibility and other issues must be thoroughly considered before defining a system.

Where possible, keep the system simple, using existing bearing materials and established drive technology. The system design must take into account the operating principles of the selected components and the effects during dynamic operation. With proper selection and design, it is quite possible to achieve sub-micron precision levels in a vacuum environment.