NANO-PRECISION MOTION IN A VACUUM

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Introduction

Nanometer management of motion is becoming more pervasive in industry as leading edge technology pursues a common trend of working on smaller and smaller scales. This trend is prevalent in numerous positioning sensitive industries, such as fiber optics, bio medical, micro machines, electronics, semiconductor, energy, optics, aerospace, Synchrotrons as well as other research and development.

Nano-positioning applications have demanding requirements that are further complicated when the management of motion is under vacuum or when requiring extended travel, finer repeatability, higher speed, greater uptime and of course, lower cost.

The challenges of engineering and selecting components that must work together in perfect harmony to achieve nanometer precision are not to be under estimated. The drive mechanism, bearings, feedback system, motion controller, kinematic structure and the environment all need to be designed to perfection to meet nanometer precision in atmospheric or vacuum environments. The vacuum challenges vary from 10e-3 TORR to 10e-12 TORR from positioning performance to outgassing challenges.

Material Selection

The first design decision for a vacuum motion system is the material of the bearings and structure. Vacuum motion systems are typically made from bare 6061 aluminum and 300 or 400 series Stainless Steel. Machined Aluminum without grinding or polishing so that it does have rolled pockets to trap air or contamination, works well and is the most cost effective material. Depending on the vacuum level even anodized stages can be used in low vacuum applications. (10e-3 TORR) Since most precision bearings in vacuum are made from 400 Stainless Steel the use of 300 or 400 SS for the motion system is recommended when thermal variation are part of the application or experiment. This allows for the bearings and structure to deviate at the same rate allowing the bearings to maintain preload.

Other common materials used for motion platforms in vacuum are steel, copper, nickel, titanium and ceramic. All of these material works well with vacuum but some of their thermal coefficients of expansion can make for creative bearing adjustments which may reduce precision.

Drive Mechanism

Ballscrew driven stages are coupled to servomotors with linear or rotary encoders providing the position feedback while stepper motors typically count motor revolutions for positioning. These stages are well suited for higher loading and velocity applications with lower resolution requirements down in the 0.5-micron range. Servo and stepper motor ballscrew stages are better suited to working in a standard atmosphere rather than in vacuum environments due to heat dissipation and the nature or their screw lubrication challenges. These motors are typically limited to lower vacuum application below 10e-7 TORR.

Linear Motor driven stages offer exceptional speed and acceleration with millions of maintenance-free cycles. These motors are linear, three phase, brushless motors, also known as AC servomotors, in which the motor coils travel over a straight magnetic track. Linear motors have high force relative to their physical size. These stages may be better suited for atmospheric operation rather than vacuum environments as they do require heat dissipation in medium to high duty cycle applications.

Piezoelectric driven stages come in basically three modes. Piezo Stacks, Walking / Screw Piezo and Linear Ceramic Servo Motors. Piezo stacks are well suited for 1 nanometer positioning when very small motion (typically 100 microns or less) is needed. Walking Piezo use Piezo Stacks with mechanical ratcheting mechanism, which allows for increased travel but reduce the life and precision due to metal to ceramic contact and mechanical hysteresis. Ceramic Servo Motors are unique in their motion acting as a spiraling friction motor, which allows for unlimited travel without mechanical hysteresis while maintaining nanometer precision.

Other beneficial performance features that differentiate the piezoelectric motor driven stages include shorter settling times (typically 2ms), large constant velocity range (from less than 1 micron per second to 250 millimeters per second with less than 0.5 % variation), no drive inertia, no servo dither and no hysteresis. These stages are well suited for ultra high vacuum environments (10e-10 TORR) due to the materials minimal heat generation and operating temperature range.

Position Feedback

Position feedback systems in a vacuum chamber have special designs to insure performance and no outgassing. The styles discussed are three of many approaches but these are tried and proven to perform at single nanometer resolutions in UHV.

Optical encoders, based on reading a physical scale, can resolve down to the nanometer level. Although the scale has a 20 micron pitch, the signal has a sufficient signal to noise ratio to allow it to be interpolated down to the single digit nanometer. (2.5nm to 5 nm resolutions depending on interpolator) These encoders work well for most applications were cost and repeatability is needed.

The next level of performance to an optical encoder with tape or glass scale utilizes a similar read head with a novel scale. Although using the same 20um pitch, it is etched directly into the stainless steel of a ring, for rotary applications, or onto a nickel plated invar spar for linear applications. The Invar scale allows for near laser precision with repeatability and accuracy due to the manufacturing technique of calibrating it with an interferometer. Placing the scale on invar greatly reduces thermal effect that influences the accuracy of other scales.

Beyond optical scale encoders, a laser interferometer can be used to provide resolutions to 38 picometers. This can provide positioning stability, on a suitable mechanical system, to the sub-nanometer levels. Using a plane mirror optical scheme in 2 axes also allows the Abbe error to be eliminated. The added advantage of the interferometer is that only the plane mirror would reside in the vacuum chamber.

Depending upon the required measurement, a single mirror can be placed in the chamber to measure from the stage to the chamber wall. Alternatively, a differential measuring scheme can be employed to measure the distance between 2 plane mirrors within the vacuum chamber. This eliminates all common mode noise sources between the stage and instrument.

Precision Bearings

Mechanical bearings suitable for vacuum applications range from recirculating ball rail, linear ball bearings, ceramic linear ball bearings and crossed roller bearings. Currently in development are vacuum chambers with air bearings that do not enter the chamber but are integrated to the motion of the application inside the chamber.

All mechanical bearings need lubrication unless the motion duty cycle and travel are minimal. To consistently meet sub100 nano-precision only the crossed roller and air bearings work well. Since the air bearing approach has not yet been productized we will discuss the crossed roller mechanical bearings.

Crossed roller bearings come in many grades of precision. It is important to use the highest grade bearings to assure precision. The better quality bearings have rollers matched in size allowing for smoother motion, less friction and less straightness deviation along the path. We have successfully used high quality 400 Stainless Steel bearings without lubrication for low duty cycle applications but this is not recommended for long term use or high duty cycle. We will further discuss various wet and dry lubrication products as well as actual outgassing data gathered by Argonne National Laboratory.

Lubrication

Vacuum compatible lubricants range from wet to dry. In the past Krytox was used with mechanical bearings and screw systems. This viscous lubricant works well for lubricating but it must be applied carefully otherwise it will cause bearings to skid and stick. We have moved away from Krytox since its outgassing affects certain experiments. The uses of dry lubricants in the form of thin films are easy to apply and offer low friction and smooth motion.
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There are many dry lubricants available for UHV but we have had great success with two types: Molybdenum Disulfide and Tungsten Disulfide.

Molybdenum Disulfide has many forms but the most convenient is a product called Aerodag M which is applied with an Aerosol Can on a clean surface. The Moly is suspended in an isopropyl alcohol which makes for easy clean up when it is incorrectly applied. The following is the specification of this dry lubricant.

Lubricant: MoS_2 (molybdenum disulfide)
Carrier: isopropyl alcohol
Binder: Thermoplastic resin
Color: Dark Grey
Friction: 0.32 static @0.3 mil
Temperature: 400 degrees F service

Tungsten Disulfide coating of the mechanical moving parts is more complex since the mechanical parts requiring lubrication need to be sent to an authorized center for application of the product. We have found that this material allows for great bearing performance as well as minimal outgassing in the most sensitive applications, which the next section will discuss. The specifications of this material are as follows:

Tungsten Disulfide in lamellar form.
Hardness - 1.0 - 1.5 Moh's scale.
Molecular Weight - 248.02.
Density - 7.4 gms/cc.
Thickness - 0.000020 inch (0.5 microns) "maximum".
Appearance - on initial application silver-gray, then polished
rhodium when burnished.
Co-efficient of Friction - 0.030
Carrier - Dry air, no binders or adhesives.
Adhesion - mechanical - molecular interlock.
Chemical Stability - inert, non-toxic, corrosion resistant.
Magnetism - non-magnetic.
Vacuum Environment - -350°F to +2400°F (-188°C to +1316°C)
temperatures of 10 -14 TORR.

Vacuum Outgassing Characteristics

A stage, Model number AI-HR4-2500E-UHV, underwent a series of laboratory tests to determine the vacuum characteristics at Argonne National Laboratory. These tests measured the outgassing rate and the residual gas spectrum during the test sequence. This stage was prepared with a commercial tungsten disulfide dry film lubricant on the rolling races to avoid using grease in this UHV application.

The outgassing rate measurement used the simple rate of rise method. Knowing the volume of the system and the pressure rise over a one minute time period, the outgassing rate can then be computed. This measurement was performed at a number of points during the test sequence. The arrangement of equipment is shown in Figure 1. The manual gate valve above the turbo pump is used to perform the rate of rise measurement.

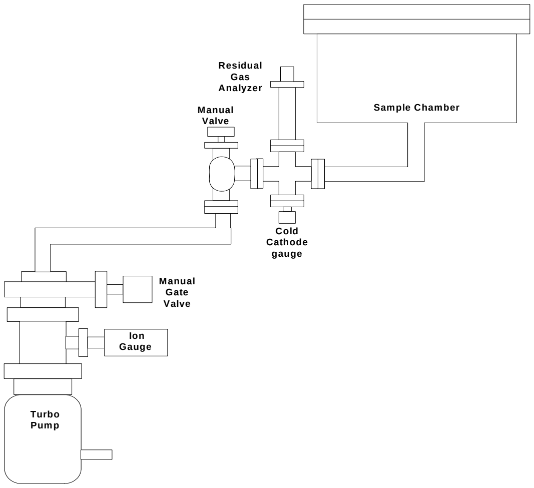


Figure 1 Test Set-up

The test sequence was performed twice: first time with the aluminum chamber empty and second with the stage in place. This allowed the chamber background to be subtracted out. The order of events in the sequence is: (1) the chamber was opened

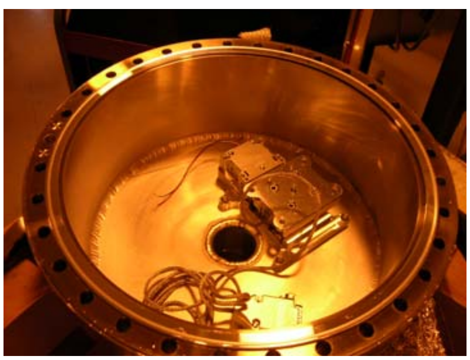
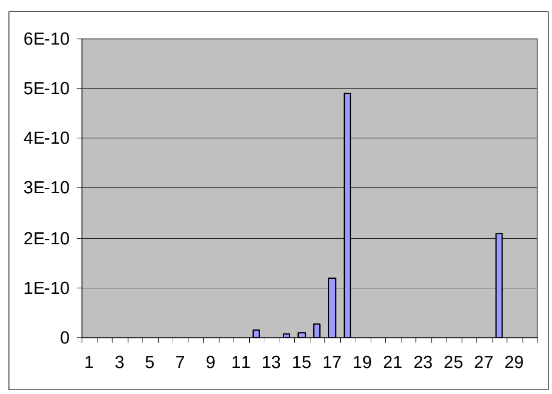


Figure 2

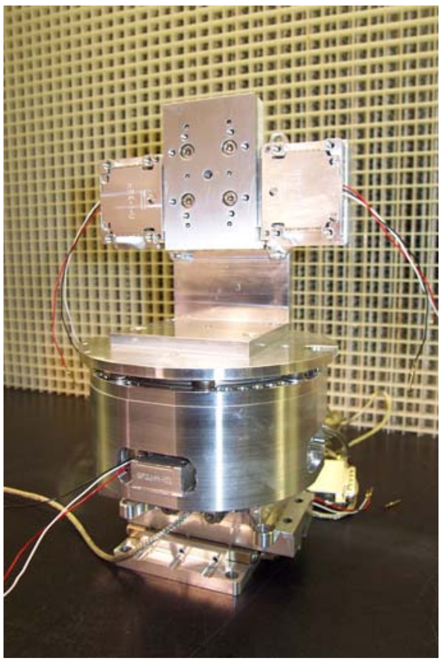
and the stage placed inside. Figure 2 shows the stage inside the metal sealed chamber. (2) After sealing the chamber it is pumped down and data taken in the first couple hours. (3) Take data after pumping at room temperature overnight. (4) Start bake out by increasing the temperature to 50 C, to prevent aluminum flanges from leaking, and then hold temperature 4 hours where data is collected. (5) Increase the temperature to 125 C, hold temperature for overnight. (6)The next day collect data at the elevated temperature. (7) Decrease the temperature to 50C, hold for 4 hours and collect data. (8) The heaters are turned off and the system is allowed to cool overnight. (9) On the last day with the system stabilized at room temperature the last data is collect. The set of data collected at each point is pressure, temperature, rate of rise data, and the spectra from the residual gas analyzer.

Initial and in-process data is collected for the stage. It is the final after bake data that is most significance and it is shown below. The final pressure of the chamber and the stage was 4 x 10^{-8} TORR where the empty chamber was 1.8 X 10^{-8} TORR. The final outgassing rate of the stage/chamber was 2.3 X 10^{-8} TORR-lit/sec when the empty chamber is 5 X 10^{-9} TORR-lit/sec. The spectra of the residual gases are shown in figure 3. Notice that there is no measurable species above the 28 peak. This system is not showing a hydrogen (2) peak since the system is largely aluminum and there is less hydrogen dissolved into aluminum as there is in stainless steel. What this does show is an absence of hydrocarbons. Hydrocarbons are indicative of oil based contamination and the residual gas analyzer did not indicate any measurable amounts.



Kinematic Structure

Multi axis systems for vacuum are more prevalent with increased needs for nano-science. Serial kinematics works well for single, two, three or four axis systems but the design and machining of these axes is critical when reducing errors such as sine cosine and Orthogonality of stacking the stages. Also, resonant frequency can be an issue if the design fails to be engineered for motor, bearing and material structure. On top of all these concerns are the duty cycle and the potential for thermal deviations caused by the motor and stacking the axis in a manner that increases the motion forces.



4-Axis 10e-10TORR System

When extreme precision is needed for five and more axes the parallel kinematic solution is the best choice. With parallel kinematic solutions the error quotient is not additive thus reducing the concern for serial kinematic sine cosine and Orthogonality error quotient.

Parallel kinematics typically takes up less valuable space in a chamber versus serial kinematics. Hexapods with forward and inverse kinematics have velocity and path motion that can enhance motion profiles that serial kinematics may not be able to handle due to sub micron errors associated with the stacking of stages.

AI-HR2-UV Hexapod

Summary

Motion systems for nanometer precision have many critical components that must work well together for nanometer precision and when you place these components in a UHV chamber these components need to be carefully re-engineered to assure heat dissipation, outgassing and precision motion . We have not discussed in this paper the necessity of having a capable motion controller but this is the most important key to nanometer precision. Closing the loop between the motors and encoders with high speed interpolation is a must for nanometer precision.