ARUN MICROELECTRONICS LTD

Vacuum Compatible Stepper Motors

APPLICATION NOTES

ISSUE 20220314

1. Operation of Stepper Motors In-Vacuum

It is assumed that the reader is familiar with the production of UHV and the handling of UHV components.

This note does not attempt to describe the theory of operation of hybrid stepper motors.

1.1 The Vacuum Environment

The successful application of vacuum stepper motors requires an appreciation of their thermal and mechanical properties. Compared to motors operated in air, the available cooling means for motors in vacuum are much less effective, and until the development of the B-series motors continuous operation was difficult to achieve.

Operation at low temperature improves the outgassing performance of motors. For this reason, minimum running times and motor currents should always be pursued. Selection of the largest motor possible for the application will result in longer running times, lower motor temperature and lower outgassing. This is because of the larger mass and higher efficiency of larger motors.

Stepping motors only perform useful work while the load is moving. This may only be for a period of a few milliseconds for each step. If the SMD3 stepper motor drive is used, acceleration current is applied immediately when the motor starts moving. When the motor stops after the deceleration, two additional states must be traversed before the acceleration current is reduced to hold current [IH]. First, a configurable delay [PDDEL] during which acceleration current continues to be applied (called 'standstill' state), followed by a configurable delay [IHD] during which acceleration current is reduced to hold current (called 'going to standby' state). If your application allows it, set [PDDEL], [IHD] and [IH] to zero in order to reduce run current to zero as quickly as possible after stopping which minimises motor temperature rise. See the SMD3 user manual for further information.

At low speeds, the torque of a motor is roughly proportional to the phase current but the motor power is proportional to the square of the current. Where the load inertia dominates the dynamics of the system it is often possible to reduce the phase current, provided the motor is accelerated more slowly.

Many applications that appear to require continuous running, for example, substrate rotation for ensuring uniformity of deposition or implantation, can be equally well performed by intermittent short periods of stepping at a low duty cycle. This will reduce the temperature rise.

Where intermittent motion is required, mechanisms should be designed with balanced loads whenever possible, to eliminate the torque required to hold them stationary. Alternatively, increase the static friction in the system or add reduction gearing so that the motor detent torque will hold position without power.

Maximum efficiency of AML motors is achieved between 500 Hz and 1 kHz full-step rate using the SMD3 drive.

1.2 Temperature Rise

The maximum recommended operating temperature of AML motors is 190 °C, as measured by the embedded Type-K thermocouple. Take care to ensure that any measuring equipment connected to the thermocouple is not affected by the high electrical noise environment within the motor during operation.

Irreversible deterioration of the winding insulation will begin to occur above 230 °C and the motor may subsequently produce larger amounts of gas, even at lower temperatures.

The temperature rise at step frequencies above 1 kHz will progressively reduce with a typical drive, which will be unable to establish the set phase current during the step period.

Continuous running with low outgassing can readily be achieved at medium phase currents. Run times at higher currents can be increased by additional heatsinking at the flanged end of the motor.

The predicted temperature rise will be increased if radiation from other sources within the vacuum chamber is incident on the motor. Screening may be necessary.

1.3 Outgassing

Newly installed motors will outgas, mainly due to water-vapour retention in polyimide. As this material is microporous the water is released rapidly and the rate will subside after a few hours. The rate may be accelerated by running the motor to self-heat it.

1.4 Baking Vacuum Systems Containing Motors

Vacuum-baking of AML Motors at up to 200 °C is permissible, and a 24-hour bake at this temperature will normally reduce the outgassing to its minimum, provided there is pumping capacity of 100 litres at the site of the motor. Outgassing test chambers with limited conductance between measuring points will require baking for several days or weeks to fully outgas a motor.

Motors are typically operated at some distance from the chamber walls, which is where heat is applied and the bakeout temperature is most often controlled. If the thermal conductance from the chamber to the motor is low the motor may not reach the desired temperature. Fortunately, the motor thermocouple allows its temperature to be monitored and controlled to ensure adequate degassing.

If the temperature indicated by the motor thermocouple during bakeout is not high enough when the bakeout period is well advanced, it may be increased to 200 °C by using the SMD3 bake mode. This energises both phases and keeps the motor stationary in a half-step position. Phase current is modulated to achieve the programmed setpoint. Keeping the motor hot by this means while the rest of the vacuum system cools is recommended, as this will prevent condensation on the motor. This is important since the motor is likely to run hotter than the chamber in most applications.

Where internal infra-red heaters are used for bakeout, it is advisable to shield the motor from direct radiation and to achieve the desired temperature during bakeout by running the motor.

1.5 Corona Discharges

Switch-mode stepper motor drives have source voltages of up to 100 V which may be sufficient to produce a discharge at high pressure. This is most likely to occur on adjacent pins of the feedthrough but un-insulated joins in the motor wiring or small holes in the insulation are other possible sites. The drive may not be protected against this type of discharge and may be damaged. The insulation material near a persistent discharge will progressively deteriorate.

1.6 Low-temperature Operation

Standard AML motors are suitable for operation at −65 °C. Low-temperature versions are available, which are suitable for use at −196 °C. The leads of the motor will be very brittle at low temperatures and should not be allowed to flex. The normal mechanical and electrical properties of all materials are recovered on return to room temperature.

Because the resistance of the windings at low temperatures is small, the efficiency of the motor is much greater than at normal temperatures. A resistance of a few ohms should be connected in series with each winding, in order to present a normal load to the SMD3. Drives which are voltage sources and which rely solely on the resistance of the motor to define the phase current should not be used for low-temperature applications.

1.7 The Magnetic Environment

Motors should not be operated in fields of greater than 50 millitesla (500 gauss), as this will affect the performance while the field is present. Fields significantly greater than this may cause partial de-magnetisation of the rotor, reducing the torque. Demagnetised motors can be restored by AML.

The leakage field of a motor is of the order of 1 microtesla (10 milligauss) at 10 cm from the centre of the motor in an axial direction and is present when the motor is not powered. During operation, an alternating component is added at the step frequency and its harmonics up to a few kHz. The field is easy to screen with Mumetal or similar high-permeability foil at the sides of the motor but is more difficult around the projection of the shaft. Early consideration of the interaction of stray fields on nearby equipment is recommended.

1.8 Adverse Chemical Environments

AML stepper motors are specified for use in a clean UHV although they are often used in deposition systems. Where it is possible to screen the motor from the line of sight of the deposition source this should be done. Where chemical vapours are being used careful consideration of the effect on the motor materials will be required. AML are generally unable to answer on the effect of exotic chemicals but may be able to provide sample materials for test. The materials used, in approximate descending order of exposed surface area are:

Polyimide
Diamond-like Carbon
Stainless Steel (End Caps) 304L, 316L
Silicon Steel
Stainless Steel (Rotor Shaft) 1Cr18Ni9Ti
Stainless Steel (Bearings) X65Cr13, X105CrMo17, X5CrNi1810
Neodymium
Aluminium Alloy 6061
Poly Ether Ether Ketone (PEEK) 450G
Alumina Ceramic
Silicon Nitride Ceramic *(Hybrid Bearing Option)*
Silver
Fluorinated Ethylene Polymer (FEP) *Not used on radiation-hard motors*
Copper
Chromel/Alumel *Chromel and Alumel are registered trademarks of Hoskins Manufacturing Co.*

Bearing lubrication: NyeTorr® 6300 Ultra-low outgassing UHV grease.

1.9 Care and Maintenance of VCSMs

VCSMs are inherently robust and have only a single moving component consisting of a simple rotor assembly, supported on ball bearings. The maximum speed of this type of motor is very low so that the bearings have an extremely long predicted service life in vacuum. There are no commutators, slip rings or any other components having sliding contact between surfaces. Given reasonable care in handling there should be no need for any maintenance.

Stepper motors should not be disassembled as this partially demagnetises the permanent magnet in the rotor and permanently reduces the torque.

Vacuum motors must be de-magnetised before disassembly and cleaned and re-magnetised after repair. For these reasons, motors with faults will need to be returned to AML for repair. The following notes offer guidance on the avoidance of the most common problems and diagnostic advice.

1.10 Debris Inside the Motor

Foreign material can enter the motor via the pumping holes and gaps in the bearings. Particles of magnetic materials are particularly likely to be attracted through the pumping holes and they eventually migrate into the gap between the rotor and stator. They usually cause the rotor to stick at one or more points per revolution and can often only be felt when rotating in a specific direction. Fortunately, the larger motors have enough torque to grind them into a dust.

1.11 Overheating

Motors which have been heated to 230 °C will produce a much greater gas load thereafter, although their electromechanical performance may not be affected. Rewinding is practical provided the windings are not discoloured and the vacuum performance will be subsequently improved. If the windings are darker than a golden-brown colour the motor will not be repairable. In extreme cases, the insulating material will ablate and deposit itself as a yellow powder inside the motor case and on any cool surfaces in line with the pumping holes.

Motors can overheat extremely quickly in vacuum. This is very unlikely to happen with a properly connected SMD3 drive. Never use a drive capable of providing more than 1A of phase current and ensure that the drive current is removed as soon as the indicated temperature exceeds 190 °C.

2. Design of Mechanisms for use with Vacuum Compatible Stepper Motors (VCSMs)

The following section is an introduction to this topic and is intended to indicate the major mechanical and vacuum considerations for various types of mechanisms. A working knowledge of mechanics and vacuum construction techniques is assumed. AML supply a range of standard mechanisms which can be customised and also design special mechanisms and components.

2.1 Rotation (Position Control)

The load inertia coupled to the motor shaft should ideally be small compared to the rotor inertia of the motor. Load inertia up to two or three times that of the motor can be driven, without a significant difference to the maximum start speed and acceleration which is achieved by the unloaded motor. Load inertia of around ten times that of the motor can be driven with absolute synchronism, provided care is taken over-specifying the micro-step and acceleration parameters. Larger inertia loads should be driven through reduction gearing.

Significant loads should have their centre of gravity on their axis of rotation, unless they are rotating in a horizontal plane.

Angular resolution at the motor shaft is limited to a single step of 1.8°. The actual rest position within the step is determined mainly by the load friction and any torque imposed by the load on the motor at rest. If the rotor position is displaced $\theta°$ from the nominal step position the restoring torque increases approximately in proportion to $\sin(100 \times \theta)°$. The maximum torque at the half step position is either the detent torque or the holding torque, depending on whether the motor is powered at rest. If the static friction and any torque due to an unbalanced load are known, this allows the rest position error to be estimated using the above approximation. The friction within the motor bearings is very low, so that a completely unloaded D42.2 motor will normally settle within 0.2° of the desired position if brought suddenly to rest from full stepping at 300 Hz.

Angular resolution may be improved by reduction gearing: this is discussed below.

Increasing angular resolution by step division is not recommended for vacuum applications, since the motor must be continually powered to maintain the micro-step position. The absolute improvement which could be gained by this method is small because of the increased significance of the uncertainty in the rest position.

2.2 Rotation (Speed Control)

In some applications, the precise position of a rotating load is not important or can be deduced by other means, but the speed of rotation may need to be controlled very precisely. Beam choppers and sample rotators for control of deposition uniformity are applications of this type. An increased load inertia may be desirable to smooth out the stepping action of the motor. Loads of up to about 1000 times the inertia of the motor can be controlled by using long acceleration ramps. Some steps may be lost during acceleration and retardation of such loads, but precise synchronism at constant stepping frequency is easily achieved and recognised.

Significant rotating loads should be balanced, at least to the extent that the torque presented to the motor shaft is less than the detent torque of the motor. The motor torque requirement will then be dominated by that required to accelerate the load.

2.3 Translation

Translation may be produced by a leadscrew and nut, wire-and-drum or rack-and-pinion mechanisms. The choice depends on the precision, length of travel, force and speed required.

Leadscrew-based translators are capable of exerting forces of kilograms with resolutions of a few microns per step. Accurate leadscrews are practical up to 300 mm long. With anti-backlash gearing between the motor and leadscrew, a resolution of one micron is practical. Anti-backlash nuts are not normally necessary for vertical motions. If a conventional nut is used with the leadscrew, the load will be dominated by friction, especially if there is a reduction gear between the lead screw and the motor shaft which reduces the reflected load inertia. Because of the lubrication restrictions and the slow speeds of UHV mechanisms, static friction is usually much more significant than dynamic friction. The optimum material for nuts is phosphor bronze and for leadscrews is stainless steel with a diamond-like coating (DLC). DLC has a very low coefficient of friction in vacuum. Burnishing or sputtering a layer of pure Molybdenum Disulphide on the leadscrew may be useful in reducing friction and wear. The typical coefficient of friction between these materials is 0.1 and typical efficiencies are 40% with ground trapezoidal threads. The gas load generated by frictional heating of the leadscrew is usually somewhat less than that of the motor. This may be reduced by changing to either a Molybdenum Disilicide or Tungsten Disilicide leadscrew coating.

For short translators with resolutions of a few microns, AML can supply motors with integral leadscrews formed on an extended motor shaft. This eliminates the need for a coupling arrangement and for the additional bearings which would be required to support a separate leadscrew.

Recirculating ball nuts for vacuum use are available. These offer much higher efficiencies but have a very high cost. They produce a very low gas load due to their low friction and can be used to exert forces of tens of kilograms. They can be loaded with selected balls to reduce backlash to an extremely low level. The form of the associated lead screw is special and longer lengths are available.

The frictional losses in drum or rack drives are lower than in conventional leadscrew drives and considerations of inertia usually dominate. Rack and pinion drives are suitable for travel up to a few hundred millimetres and wire-and-drum mechanisms may be made several metres long. The repeatability and backlash of all these alternative translation drives are much worse than with screw-driven schemes.

2.4 Linear Guides

Low-cost translation mechanisms can use simple bushes running on ground stainless steel rods. A variety of carbon-reinforced polymer materials, such as PEEK, are suitable for the bushes, although these are more expensive than phosphor bronze.

'V' groove rollers, tracks and crossed-roller guides are suitable for more accurate translators. The former has the advantage of being practical to 1 metre and have minimal overall length for a given travel. Crossed-roller slides are more rigid and can support larger loads, but at higher cost. Both types have preload adjustments. 'V' rollers have smaller load-bearing surfaces and only have a rolling contact at a single point and are consequently liable to greater wear if heavily loaded.

2.5 Reduction Gearing

The inertia of loads coupled by reduction gearing is reduced at the motor in proportion to the square of the reduction ratio. Where reduction gearing is used for load matching, the spur gear meshing with the motor pinion will normally dominate the load inertia and it is important to keep its diameter small. Anti-backlash gears and standard pinions should be used in the gear train to damp any resonances in the mechanism. Gears for use in UHV should be designed for low friction without lubrication and with dissimilar materials in contact to avoid cold-welding. Nitrogen ion-implantation of the rolling surfaces or complete Titanium Nitride coating of gears are effective means of achieving this and other desirable properties in all-stainless-steel gear trains.

2.6 Bearings

Bearings for use in UHV should be unshielded and have a stainless-steel cage and race. The balls should be either stainless steel coated with some other material or solid ceramic. As an alternative, all-stainless bearings having a PTFE composite component in the race (which is designed to transfer to the balls), which are also suitable.

3. Resonances

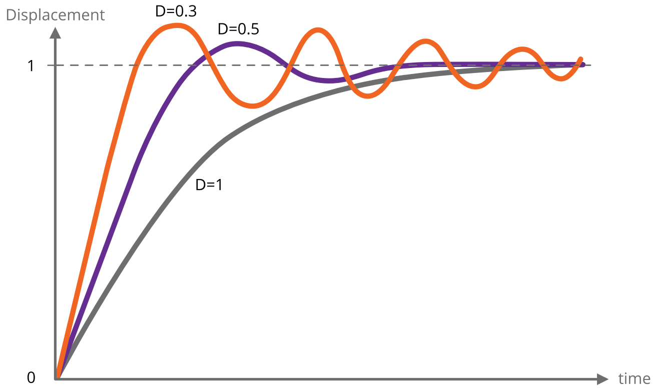
The most common application problems with stepper motors are concerned with resonances.

Stepper motors are classic second-order systems and have one or more natural resonant frequencies. These are normally in the 50 – 100 Hz region for unloaded motors. Operation at step rates around these frequencies will excite the resonances, resulting in very low output torques and erratic stepping. Another set of resonances can occur in the 1 – 2 kHz region, but these do not normally present any practical problems.

3.1 The Effects of Load Inertia, Friction and Drive Characteristics

The primary (lower) resonant frequency cannot be stated with any precision, since it is modified by the friction and inertia of the load, the temperature of the motor and by the characteristics of the drive. Coupling a load inertia reduces the resonant frequency and decreases the damping factor. Load friction increases damping. Because the drive circuits of the SMD3 produce a controlled phase current this produces heavy damping. Drives that are voltage sources and which rely on the motor winding and other resistance to define the current have a lower damping factor.

The effect of changing the damping on the single-step response of the motor is shown in the diagram.



3.2 Control of Resonances

The simplest method of controlling resonances is to avoid operation of the motor close to the resonant frequencies. It is usually possible to start a motor at rates in excess of 300 Hz if the load inertia is small, thereby completely avoiding the primary resonance. Resonances are not usually a problem when the motor speed is accelerating or retarding through the resonance frequency region.

If it is necessary to operate at slow speeds or with large load, using micro-stepping helps. It effectively increases the stepping rate by the step division factor and reduces the amplitude of the transients that excite the resonances. This is shown in the diagram below. Because both phases are energised in micro-stepping there are some other processes of interchange of energy between the windings which do not occur in the single-step mode and these increase the damping factor.

In particularly difficult cases modifying the step frequencies at which transitions of the step divisions (micro-stepping modes) occur can be useful.

Be careful not to specify step division at excessive frequency, as this reduces the available torque. The frequency of step division is the product of the step frequency and the number of micro-stepping in a full step. As a general guide, 500 Hz is the maximum useful limit.

A typical motor response to a single step and to a single step subdivided into eight micro-steps is shown in the diagram.