Motors for Positioning in Vacuums

by Richard Halstead
President
Empire Magnetics, Inc.

Operating a motor in a vacuum is often perceived as a design challenge. Among engineers, the problems -- outgassing, contamination and temperature -- are well known. What is less well known is that there are now well-developed solutions to each of these problems.

Historically, the ability to move or position samples, products, mirrors and sensors in a vacuum area (some of the most common requirements) has been accomplished with drive mechanisms and motors located outside the vacuum chamber. In this type of control solution, the drive mechanism transmits its motion through the vacuum chamber wall using sealed couplings.

There are a number of disadvantages to this traditional vacuum-motion control approach, however. One major problem is that putting the motors external to the vacuum chamber and using magnetic or mechanical feed-through mechanisms forces the engineer into the use of a limited number of design configurations. For instance, it is very difficult to implement an X-Y stage (in which one stage moves on top of the other) inside a vacuum chamber when external motors are being used, since the mechanical components used to transfer motor power greatly restrict the design possibilities. Further, the accuracy, repeatability, and resolution of the positioning system inside the vacuum chamber are compromised.

On the other hand, placing the motor directly into the vacuum frees the engineer to use a larger number of physical arrangements, since the motor cables can be routed in any number of ways without inhibiting the activity in the chamber. By directly coupling the motor to the load, the accuracy and other system specifications can also be vastly improved. Finally, because mechanical feed-throughs for the vacuum system are often as expensive as a vacuum motor in its entirety, a system that features an internally-placed motor often costs less than the externally-mounted alternative.

For all these reasons, more and more vacuum applications are utilizing specialized motors that have been designed for use in a vacuum, and which take into account the unique environmental conditions that are present. Standard motors are not an appropriate choice for a vacuum application. In general, standard motors will not survive in a vacuum of 10^{-4} Torr or lower. The primary reason is that the lubricants in the bearings will vaporize and the insulation materials of the motor and cable will evaporate, a phenomenon known as "outgassing." Outgassing within a vacuum chamber is obviously very negative: in addition to destroying the motor, the vaporized materials condense on precision optical components and delicate mechanical devices, thus fouling the application.

Some materials like petroleum-based grease vaporize so quickly that they literally create clouds of vapor in the vacuum chamber. Other materials vaporize more slowly, but can become an application nightmare. Silicone is one of these nightmares, since once a vacuum chamber has been contaminated with silicone, it is nearly impossible to clean it all out, and it will continue to spread to anything and everything that is placed into the chamber.

Motor cooling in a vacuum is also a problem. Conventional motors are cooled primarily by convection into the air that normally surrounds them, and to a lesser degree by conduction through the mounting surface. When a motor is energized in a vacuum, convection cooling is not available, and heat is dissipated primarily by conduction from the motor to the mounting structure. As a result, when operating a motor in a vacuum, provisions for heat exchange and higher temperature operation must be made.

It's one thing for a motor to operate successfully in a vacuum, and another for the process itself to be successful with the motor present: consequently, leakage is another problem with motor operation in a vacuum. Even if a standard motor does not outgas contaminants in a vacuum, it is likely that the vacuum process will be hampered with the motor present. For example, a step motor that is not properly treated will "leak" air molecules long after the vacuum is applied. Leakage is the slow release of captured or clinging gas molecules from minute cracks in the motor laminations, windings, bearings and metal surfaces. The leakage occurs when the surfaces of these porous materials are not treated, resulting in unacceptably long pump-down time or an inadequate vacuum level. This leakage is a mechanical problem as opposed to the materials problem of outgassing.

Finally, high voltage exposed conductors on motors in a vacuum can create corona effects. At certain vacuum levels, the rarified air will easily ionize, and current will flow between unprotected high voltage conductors (this principle was the basis of the well-known "electron tube").

The solutions to these vacuum chamber/motor design problems -- outgassing, cooling, leakage, and corona effects -- are all to be found in a properly-designed vacuum motor. Outgassing, for instance, in which motor materials such as bearing grease, paper slot liners, conformal coatings, winding insulation, and many kinds of cements or glues vaporize entirely or partially, can be prevented by the careful selection of appropriate materials. Teflon is a commonly-used material in vacuum applications, as it is quite stable, has good temperature characteristics, and is readily available at a reasonable price. Most metals are acceptable for use in a vacuum (exceptions include cadmium and zinc), but stainless steel is a particularly good material for vacuum/motor applications.

In general, material outgassing rates are not significant between atmospheric pressure and 10^{-4} Torr. In this range, many commercial plastics are usable, but lubricants usually need to be selected carefully. If the vacuum is in the 10^{-7}Torr range, most natural materials must be eliminated, and only a limited number of plastics are usable. At this range, vacuum lubricants are essential. At 10^{-9} Torr, most plastics are excluded and dry lubricants must be used.

Outgassing can also result from a lack of motor cleanness. Motor materials are subjected to a variety of contaminants during the manufacturing process, and trace materials are always left behind: steel is exposed to cutting oils, plastics are lubricated when extruded from dies, and epoxies are mixed with solvents. Additionally, motors held by human hands will leave a residue of oil behind. Varying degrees of vacuum purity are required by different applications, but if system components are not properly cleaned, there will definitely be outgassing of various contaminants into the vacuum chamber. When a customer has rigid specifications regarding chamber contamination, Empire Magnetics puts its vacuum motors through a proprietary extraction and cleaning process that gets into the deep crevices that vapor degreasing cannot reach, accelerating molecular changes in contaminants that would otherwise outgas, and renders them inert. In general, the sensitivity of vacuum environments usually requires the use of motors that have been constructed of non-volatile materials, vacuum baked, processed to extract contaminants, and then sealed.

In addition to being a problem for motor operation in and of itself, high temperatures cause accelerated outgassing. To prevent motor failures and inhibit outgassing, the selection of the drive type and the drive voltage can greatly reduce the motor's operating temperature. High voltage PWM (pulse width modulation) drives heat the motor more than low voltage linear drives. Bipolar drives using all of the copper in the motor at one time generate less heat than unipolar drives that use half of the copper. Further, drives with automatically reduced standby currents, or servo systems that reduce current when the motor is not moving, also produce less heat.

Motor temperatures can be monitored with thermistors, thermacouples or RTDs (resistance thermometer device), and the information can be used to modulate the use of power to the motor, in an effort to keep the temperature within the safe operating range. The use of cold plates or cooling jackets can be considered in cases where substantial amounts of power must be generated, and where there is thus a consequent rise in temperature. One successful cooling jacket designed and used by Hughes Aircraft used the vapor from liquid nitrogen and was controlled by a feedback system that monitored the motor temperature. This system held the temperature to a comfortable operating range, even though the motor was heavily loaded for three months of continuous satellite testing.

Leakage in a vacuum/motor application can be overcome by eliminating the cracks, crevices and other areas that trap gasses within the motor. If the motor is not properly treated before installation in a vacuum, the laminations, windings, bearings and even metal surfaces will release the air molecules trapped in their surface cracks. The motor will then require a significant period in a vacuum to release all of its trapped air, interfering with the need to reach a desired vacuum level in a timely fashion. Leakage can be minimized by selecting fine machine finishes that hold less air. For instance, porous metals typically require cleaning and sealing, and machined metals are preferable to castings; if castings are unavoidable, they should be modified with a machined finish. Even still, additional cleaning may be required depending on the level of vacuum required. To further reduce leakage, blind screw holes should be turned into through-holes, laminated structures should be vacuum-impregnated, and appropriate sealers should be used on all surfaces. To prevent the corona effect that can be generated by high voltage, exposed conductors must be insulated with appropriate materials to prevent arcing.

Because each vacuum application has differing requirements, there are a number of different vacuum-rated motor grades available. The following are three of the most common types:

- Commercial grade. This motor will survive in a vacuum down to 10^{-7} Torr, provided the motor does not exceed its rated operating temperature. Not specially treated to reduce outgassing. Built with materials that will not evaporate quickly in a vacuum.
- Standard grade. Built with the same materials as a commercial grade motor, but cleaned in an ultrasonic cleaner and vapor degreaser, vacuum baked, and sealed to minimize recontamination.
- Laboratory grade. Cleaned and baked like the standard grade, but also undergoes an extraction process to remove contaminants. Motor windings often use Class H insulation, which allows winding temperatures 50° C higher than the other grades. Motor should be handled under clean-room conditions, with new nylon gloves (even clean rubber gloves would contaminate the motor).

Prior to installation of any motor in a vacuum, careful consideration of your particular requirements will assure that the system will be appropriate to your needs, cost-effective and durable.