Motor Designs To Survive Hostile Environments

A new generation of step motors is allowing motion control applications to prosper where they were previously impossible or, at best, very difficult. The reason? Previous step motor designs were developed for the relatively "benign" conditions in a factory. New step motor designs -- specially developed for motor-hostile environments -- can reliably withstand the effects of radiation, underwater operation, vacuum operation, and extremely high and low temperatures, among other conditions. Accordingly, these motors are the key to a wide range of new motion control opportunities.

VACUUM MOTORS

The problems inherent in operating a motor in a vacuum -- outgassing, contamination and temperature -- are well known to design engineers. Solutions are less well known.

Common requirements for vacuum operation include the ability to accurately move or position samples, products, mirrors and sensors. In the past, this has often been accomplished by trying to evade the effects of the vacuum, by locating drive mechanisms and motors outside the vacuum chamber. The drive mechanism transmits its motion through the vacuum chamber wall using sealed couplings and magnetic or mechanical feed-through mechanisms.

One major problem with this approach is that the engineer has a limited number of design configurations he can consider. It can be very difficult to implement an X-Y stage (in which one stage moves on top of the other) inside a vacuum area when motors are outside the chamber, since the mechanisms used to transfer motor power to the top stage must also accommodate the motion of the bottom stage. The accuracy, repeatability, and resolution of the positioning system located inside the vacuum chamber can be heavily compromised.

In contrast, placing the motor directly into the vacuum allows the engineer to consider a larger number of physical design arrangements without compromising the motion control activity inside the chamber. By directly coupling the motor to the load, the accuracy, repeatability and other system specifications can be vastly improved. Because mechanical feed-throughs are very expensive, a system that features an internally-placed motor often costs much less than the externally-mounted alternative.

Ordinary motors will not survive in a vacuum application of 10^{-4} Torr or lower. The reason is that the bearing lubricants will vaporize and the motor's and cable's insulation materials will evaporate in a phenomenon that is known as "outgassing," resulting in destruction of the motor. Outgassing further results in vaporized materials condensing on any precision optical components or delicate mechanical devices that are present. Among other materials commonly found in a standard motor, bearing grease, paper slot liners, conformal coatings, winding insulation, and many kinds of adhesives vaporize in a vacuum.

Some materials are particularly inappropriate for a vacuum chamber, since they outgas so quickly that clouds of vapor are created. Other materials, such as silicone, are an even bigger problem: silicone is nearly impossible to remove by cleaning, and will continue to spread throughout the chamber, contaminating its contents.

Air leaking from the motor itself is another frequent problem with vacuum motor operation. A step motor that has not been adequately prepared will leak air molecules long after the vacuum is applied. Captured or clinging gas molecules slowly emanate from minute cracks in the motor laminations, windings, bearings and metal surfaces. If these porous materials are not treated, an unacceptably long pump-down time or inadequate vacuum level can result.

Motor cooling in vacuums is another problem. Standard motors are generally cooled by convection into the surrounding air, and less significantly, by heat conduction through the motor mounting surface. Convection cooling is not available in a vacuum. Heat is dissipated mainly by the least-efficient method: conduction through the mounting structure. As a result, vacuum operation can require special cooling devices and higher temperature operation.

Finally, corona effects can result from exposed high voltage conductors. At certain vacuum levels, the rarified air ionizes easily, and current can arc between unprotected high voltage conductors.

Solutions to all of these vacuum motor problems -- outgassing, cooling, leakage, and corona effects -- have been answered by new designs in vacuum motors. Outgassing, for example, can be prevented by the selection of materials with low vapor pressure. Teflon is one such stable material. Most metals are also suited to use in a vacuum (exceptions include cadmium and zinc). Stainless steel is a particularly good material for vacuum applications.

Material outgassing rates are generally not significant between atmospheric pressure and 10^{-4} Torr. In this range, many commercial plastics are usable, although lubricants usually need to be selected carefully. In vacuums approaching 10^{-7} Torr, most natural materials must be eliminated in a motor, few plastics are viable, and vacuum lubricants are mandatory. At 10^{-9} Torr, almost no plastics can be used, and dry lubricants are required.

Scrupulous motor cleaning limits outgassing problems. Trace materials from the motor manufacturing process are always present from a variety of sources: cutting oils are used on steel, lubrication is left on plastics when extruded from dies, and solvents are mixed with epoxies. Human hands leave an oil residue behind. Outgassing contamination is not critical in all applications, but if system components are not properly cleaned, outgassing of various contaminants will definitely result.

Manufacturers that specialize in motors for vacuum environments, such as Empire Magnetics, subject motors to a cleaning process that gets into crevices that vapor degreasing cannot access, accelerating molecular changes in materials that would otherwise outgas, making them inert. The sensitivity of vacuum applications usually requires the use of motors that have been constructed of non-volatile materials, vacuum baked, processed to extract contaminants, and then sealed.

Remedies for high motor temperatures include limiting power to the motor, and fabricating the motor with high temperature materials. A thermocouple or RTD (resistance thermometer device) can be installed in the motor to monitor temperature. The temperature information is used to modulate motor power, in order to keep the temperature within a safe operating range. When substantial amounts of power must be applied, cold plates or cooling jackets can be considered. For one example, Hughes Aircraft designed and installed a system that used the vapor from liquid nitrogen and which was controlled by a feedback system that monitored motor temperature. Even though the motor was heavily loaded for three months of continuous satellite testing, this system reliably held the temperature to a safe level.

Finally, to prevent the corona effect that can be generated by high voltage, exposed conductors must be insulated with appropriate coatings to prevent arcs.

Recent Step Motor Vacuum Applications:

Satellite testing/positioning of satellite in vacuum chamber during assembly
Observatory instrumentation/telescopes
Alignment of laser beams for research
Beam alignment during fusion research

Semiconductor manufacturing
Wide range of clean room applications for research and testing
Aircraft component testing
Superconductor research
Ion deposition equipment
Electron beam welders
Electron microscopes
Material testing facilities

WATERPROOF STEP MOTORS

Because of the preponderance of water and solvents, motion control components are often exposed to the risk of corrosion and failure. Waterproof motors are a key part of the solution to water-induced motor failure problems.

Today's waterproof motors are specifically designed to survive a minimum of 30 feet under the sea, a general industrial standard for the "waterproof" designation. These are not retrofitted standard step motors, but are truly waterproof motors, which operate very well above the waterline, too -- in a wide variety of industrial and marine settings. The motors have been fitted with redundant shaft seals, O rings, hermetic cable feedthrough, pressure equalization and other waterproofing features. Together, these design features allow a step motor to answer a design engineer's need for a motor that will not fail after even prolonged exposure to, or submersion in, most liquids.

Why don't ordinary step motors meet this need? Although these motors are the mainstays of industry and the laboratory, and provide reliable and accurate positioning for minimal cost, their design includes several weaknesses with respect to moisture. First, the coils of the standard stepper are wound with magnet wire, a solid copper wire that is coated with an enamel or varnish. While the coating process is good, it is not perfect, and the varnish always has some small pin holes in it.

When this magnet wire is wound into a coil, it is unlikely that any two pin holes will line up and "short out." Ordinarily, the spacing of the wires provided by the layers of exterior enamel prevent conduction from one pin hole to the next. However, if even a little water gets between the wires, it will promote conduction from pin hole to pin hole. In this situation, the current from the power supply will quickly destroy the motor windings. Although quality insulation and impregnation can prevent this problem, they add greatly to product cost.

Step motors are constructed of magnetic iron, and corrode very easily when subjected to moisture. To optimize torque, the gap between the rotating and non-rotating teeth of the motor is held to about .002 in. When the motor is operating, these teeth get hot, and the temperature is typically high enough to turn any water in the motor into steam. Steam is corrosive, such that the magnetic iron in the teeth rusts faster than usual.

Once the rust fills the .002 in. air gap, rotor and stator teeth begin to rub. This robs useful torque from the motor and breaks the iron oxide loose. If the rust is dry, it forms an abrasive powder, if it is wet, it forms an abrasive slurry. This oxide slurry gets into the motor bearings, and being abrasive, the bearing wear accelerates. As the bearings wear, the centering of the rotor becomes less accurate, causing the rotor to wobble as it turns and eventually hit the stator.

The combination of oxide build-up on the magnetic teeth and the loss of bearing accuracy can cause a standard step motor to fail in a period as short as two weeks. While it is possible to substitute non-corrosive metals for the magnetic iron, the metal will be more expensive, it will cost more to machine, and motor performance will be significantly degraded.

Attempts could be made to prevent moisture from entering a motor. However, standard step motors are not designed to facilitate seals. They are designed to be low in cost. As a result, proper sealing of the motor would require a complete re-design of motor parts, with an increase in manufacturing cost.

A proper design approach for motors exposed to moisture incorporates shaft seals, O rings, cable feedthrough, and pressure equalization mentioned earlier with other features that combine to create a "real" waterproof motor. For instance, while standard motor housings are made of painted cold rolled steel and/or aluminum, a waterproof motor's exterior is commonly made of stainless steel to resist corrosion.

A waterproof motor is designed to accommodate O-ring seals, allowing the watertight sealing that is not practical in a standard motor. Further, the wiring that leads to the motor coils in a waterproof motor requires a hermetically-sealed feed-through device to prevent water from wicking into the motor via the cable conductors.

Other seals are required. For instance, a threaded pipe plug at the rear of the motor is designed to allow the housing to be sealed after the motor connections have been made; this plug is also fitted with an O-ring seal. The motor shaft itself is provided with redundant shaft seals. Additional life-extending features include double insulation, coated laminations, and fittings for pressurization.

Some of the above features may be found on a standard motor, but it is the combination of all of these features together that produces a waterproof motor with a superior service life.

The existence of the new waterproof motors, and the design innovations they represent, do not simply extend motor life in moisture-filled applications -- in many cases, the applications would not be possible without this type of motor.

Recent Waterproof Step Motor Applications:

Naval/military

Aquaculture

Undersea exploration

Robotic submarines

Salvage robots

Undersea mining

Oil exploration

Sonar arrays

Communications

Automated undersea lights and cameras

Automated hydrophone arrays

Wave power generation

Flood control systems

Floating seafood factories

Hydrofoil air cushion controls

Antenna and gun pointing systems

Food processing

Cleaning, chopping, dispensing, packaging, vacuum sealing, inspecting and labeling

Corn dog machines

Automated ice cream cup fillers

Meat slicers

Pineapple coring machines

Juice box filling and sealing machines

Drug manufacturing: Pill pack sealing, packing, labeling, gene splicing microscope stages, media plate filling

Medical supply manufacturing: Artificial blood vessels, rubber gloves, sterile bandages

Automated machine tools: Mills, lathes, screw machines, grinding applications, cut-off tools

Automated inspection: Water jets and ultrasound in water tanks, inspection of nuclear reactor components

Antenna pointing systems for satellite tracking stations

Upper atmosphere wind study equipment

Railroad track grinding equipment

Pipeline welding and pipeline x-ray equipment.

Paper manufacturing

Chemical manufacturing

Film processing

Printing

Water jet cutting

Toxic clean-up equipment

RADIATION-HARDENED STEP MOTORS

Motion control in radiation-intensive environments poses one of the most difficult design challenges possible to the engineer. Conventional step and microstepping motors are susceptible to high-energy gamma radiation particles that will attack non-metallic materials. As a result, lubricants, varnish, lamination bonding, and cable insulation will all deteriorate over time and finally crumble. Also, many radiation applications include additional environment problems, such as corrosive fluids.

Radiation-hardened step motors, however, have greatly expanded the design opportunities in highly radioactive environments. A recent motion control application at Oak Ridge National Laboratory (ORNL) in Oak Ridge, TN provides a good example of the possibilities created by these new designs, even in instances where there is more than one hostile condition in the environment.

RADIATION CASE HISTORY

An important step in the fuel recycling process is the separation of spent fuel oxides from their cladding by dissolving the oxides in nitric acid. ORNL, which is responsible for the development of nuclear fuel reprocessing technologies, recently developed a new concept for performing this separation process in collaboration with the Power Reactor and Nuclear Fuel Development Corporation of Japan (PRN).

The new concept devised by ORNL is a "multistage continuous rotary dissolver" that operates as a continuous, rather than batch-type, process. The new design provides a counter-current of nitric acid that is constantly forcing the highest acid concentrations against the hardest-to-dissolve areas of the fuel pins.

ORNL was able to find only one motor design that could withstand accumulated radiation dosages of 108 and which had all of the required performance specifications, a radiation-hardened hybrid permanent magnet step motor from Empire Magnetics. The Empire motor was a "zero backlash" model that features an in-line 87 to 1 cycloidal gear reducer, a design feature that increases motor output torque without lessening motor life. A radiation-hardened brushless resolver is connected to the gearbox output shaft. The resolver provided angular positioning capability with a resolution of 4,096 steps per revolution of the dissolver drum. The motor, gearbox and resolver were mounted inside a lead box to enhance the existing radiation resistance.

The key to a successful design for the ORNL project was in the proper selection of materials. Most critical was the specification of specific polymers, not only for magnet wire and cable insulation, but also for shaft and body seals. Finally, a heavy coat of radiation-resistant polymer paint provided the outer layer of defense against concentrated nitric acid vapor.

Recent Radiation-Hardened Step Motor Applications:

- Fusion research
- Material handling
- Clean-up
- X-ray machine
- Fuel re-processing
- Fast breeder reactor
- Reactor inspection
- Beam research

EXTENDED TEMPERATURE STEP MOTORS

Extended temperature step motor applications offer some particularly extreme operating conditions. As a satellite rotates in orbit, for instance, its motors experience incredible temperature swings as they move from the blazing sun (+200° C) to freezing shadow (-200° C) in a matter of seconds. Without a very specialized motor, there is no chance that the motor would operate through a 400° temperature cycle. Other applications can be just as hostile. In infrared observatory installations, where the positioning requirements are extremely precise, the motor and adjacent instrumentation may be cooled with liquid nitrogen. For superconductor experimentation, the system may be submerged in liquid helium (20° Kelvin!) and require a cryogenic motor design. In rocket applications, the motor may be pumping liquid oxygen. Of course, there are also high temperature applications that are just as hostile. One recent high temperature example is an automated remote throttle actuator for jet engine testing, which experiences temperatures over 100° C with extreme vibration and stringent safety requirements.

LOW TEMPERATURE MOTORS/CRYOGENIC MOTORS

Contraction of metallic parts and hardening of non-metallic parts are the two primary factors that can render a step motor non-functional in low temperatures. In the instance of contraction, if motor components with critical dimensions contract at different rates, a locked-up motor may result. The resultant stress can crack metal parts made brittle by super-cooling. To combat these effects, special alloys must be selected for a low temperature motor, and all metal components must have comparable coefficients of thermal expansion.

Both cable insulation and bearing grease are susceptible to hardening at cryogenic temperatures. Dry lubrication may be required and insulation polymers must be carefully selected to retain molecular integrity through low temperature cycling.

The following case history, which combined two separate hostile conditions in the application environment, represents a typical challenge faced by the design engineer working with a cryogenic application.

CRYOGENIC MOTOR CASE HISTORY

In a recent cryogenic application, engineers at Arnold Air Force Base were were assigned to identify and qualify motors suitable for use in a vacuum chamber at cryogenic temperatures. The specification called for small motors operating in a vacuum of 10^{-7} Torr at liquid hydrogen temperatures (24^{o} Kelvin). Angular position feedback was a requirement to accommodate closed loop velocity and position controls.

Two major design problems are inherent in this type of application. The first involves the outgassing of lubrication and insulation materials at low pressure. The second problem has to do with the behavior of motor materials at very low temperatures. The stress of large temperature changes, low temperature brittleness, and varying contraction rates of dissimilar materials work to degrade the structural integrity of motors manufactured from conventional materials.

A 57 mm diameter step motor was combined with a feedback resolver to meet the unique requirements of the application. Both devices were housed in an exotic nickel chromium steel alloy frame, selected for thermal stress resistance and dimensional stability. Resolver technology was selected for the feedback system due to the similarity of resolver components with those of the motor.

To reduce outgassing at low temperature, insulation materials were made of selected polymers. Magnet and lead wire materials were carefully specified to avoid outgassing or fracture. Bonding agents normally used to build the motors were replaced with adhesives having a coefficient of thermal expansion close to that of adjacent steel components.

Each of the metal components of the motor was examined in detail. AlNiCo (Aluminum Nickel Cobalt) magnets were selected in favor of rare earth combinations, since AlNiCo retains magnetic properties better at low temperatures. Stainless steel ball bearings, lubricated with dry film, were used for the same reason. All machined metal parts were stress-relieved. The result was a design that could operate at cryogenic temperatures and within the confines of a vacuum chamber without vaporization of motor materials.

Recent Low Temperature Applications:

Satellite controls

Antenna controls
Observatory instrumentation
Liquid oxygen pumping
Superconductor research
Plasma Processing
Frozen food handling
Paper mills
Steel forming
Metal coating

HIGH TEMPERATURE MOTORS

At high temperatures, the principal failure mode is winding insulation failure and the resulting short circuit that occurs. To combat this problem, high temperature magnet wire rated to 180° C is commonly specified. Non-copper magnet wire that is protected with exotic insulation materials is used when the application involves temperatures over 200° C. Dry lubrication is used to avoid material loss.

Recent High Temperature Applications:
Furnace operation
Industrial baking
Engine testing

A step motor isn't just a step motor anymore: more and more applications require that their inherent design reflect the operating conditions present. While these reliable motors are still the workhorse for many general motion control needs, their range has also extended into hostile application environments that have expanded their value, giving the design engineer a new "old" tool.

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This article is written and provided by Rick Halstead, President of Empire Magnetics, Inc. Empire Magnetics provides quality motor products designed to perform in environments and applications where ordinary motors are unsuitable. For more information about Empire Magnetics, please visit their website at www.empiremagnetics.com.