Considerations for Step Motors in Space Applications

The application of stepper motors in space is a design problem whose complexity is frequently underestimated. While most of the research in this field has focused on bearings and lubrication, there are a number of other issues to be considered.

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The environmental challenges of space-related applications are immense, and include vacuum (10^{-8} to 10^{-12} torr), deep space cryogenic (20 Kelvin), thermal shock (sun at +200°C to shade at -200°C in one to two seconds), launch vibration, ionized particles and radiation. In addition, there is a limited power budget, severe weight and size restrictions, and reliability and life requirements.

Many engineers approach these problems by assuming that standard commercially made motors are the correct basis from which to construct a motor for space applications. Unfortunately this assumption is incorrect. Designers of commercial motors focus on reducing the cost of high volume production of standardized products. While there is certainly a drive towards 100% quality, the cost penalty for motor failure in the industrial/commercial world is relatively low and the reward for cutting costs is high. Therefore the commercial design goal is a prescription for disaster in space flight applications.

Commercial Motors in Space: A Recipe for Failure

Electrical

Electrical failure in a motor is simple. Either the wires short out, or they break and the circuits open. To improve the reliability of the motor, insulation materials can be upgraded, and special attention must be paid to the lead wire connections between the motor and the electronics. A careful thermal analysis to assure sufficient cooling capacity of the system is also important for electrical reliability.

Empire has fully reviewed redundant motors and redundant windings on each space program we have consulted on, and each time the user has ruled this approach impotent due to the weight penalty inherent in mechanically redundant motors. We have concluded the most pragmatic solution is having redundant electrical circuits in the same mechanical motor housing.

Redundant windings are required to support redundant electrical circuits. Simply winding the coils by taking two pieces of wire in hand (bifilar) offers redundancy against bad solder joints, broken lead wires and failed electronics. This does little to protect against overheating and insulation failures, and the probability of both wires being damaged in the same thermal event is great. Two separately wound coils inserted with a phase separator are less prone to fail, but a thermal meltdown is still likely to destroy both windings.

To compound matters, the slot areas of the motor were designed to have a single coil filling the entire slot. If one tries to install two coils into the slot, each coil can only contain half the normal wire amount. Since motor torque is a function of amps times the number of coil turns squared, it will take about four times as much current to achieve full torque in the motor when using a half coil. Since coil heating is a direct result of amps squared times the resistance of the coil, coil heating in a redundant winding is likely to be 4-16 times greater than a normal coil.

Oversizing the motor to make up for torque loss increases the weight nearly as much as making the motor fully redundant. To date, all space flight designs have compromised by using bifilar windings, redundant electronics, redundant lead wires and slightly oversized motors, backed up by mechanical and thermal modeling and extensive testing.

In addition to electrical shortcomings for space applications, the typical standard, commercial motor is manufactured from magnetic iron, which is stamped, coated, glued, stacked and assembled into the basic motor structure. These first few construction steps lead to an entire series of problems for motors in space applications, namely outgassing and mechanical.

Outgassing

Outgassing is a major reason why commercial motors are an inappropriate choice for a space application.

In a vacuum environment, the lubricants typically found in the bearings of standard motors will vaporize and the organic materials will evaporate - a phenomenon known as "outgassing." Some materials like petroleum based grease vaporize so quickly that they literally create clouds of vapor in a vacuum chamber. Other materials such as silicone lubricants vaporize more slowly, but result in serious application problems of their own. NASA has funded numerous studies on lubricants and much of the data can be found in NASA publication 1124 (This data is too extensive to be covered here).

The insulation material and lamination cement or glue used in the stator of a commercial grade motor are selected for rapid application and low cost, with no concern for vacuum outgassing. During the stamping operation, lubricants are added to reduce tool wear. If not carefully removed, these trace materials will outgass into the vacuum causing a variety of problems. The metal coating process traps these same die lubricants, making it more difficult to remove them, and the coating itself may or may not be vacuum-compatible.

The motor stator is manufactured by adding insulation materials around the laminated core, winding wire coils, adding the lead wires and impregnating the windings with varnish - a metal housing may or may not be used to enclose the stator core assembly. Adding to the range of problems, the varnish used to impregnate the windings is a hard material intended to maintain coil positions. This varnish is susceptible to outgassing and hides the electrical connections from inspection.

Mechanical

In addition to material outgassing, there are a number of mechanical issues related to the design and manufacture of standard commercial motors which are important to the space craft designer. The stamping operations used to provide low cost motor parts also introduce stress into the metals. The stresses will be relieved by the launch vibration and thermal cycling experienced in space, which cause the parts to change their mechanical shape. Motor failure is a likely result.

Broken shafts are typically due to weight and size restrictions placed upon the designer. However even a slight misalignment between the motor and a rigidly coupled load will bend the shaft as it is rotating. This bending fatigue is aggravated by snap ring grooves or machined cuts, and brittleness at cold temperature. When gears are used to multiply motor torque, the potential for shaft breakage increases.

The shock, vibration and thermal cycling common in space, coupled with improper material selections or treatments, can cause severe metal distortion. Warping can cause mechanical lock up of the motor. Thermal cycling and differential material expansions can also cause motor lock up.

The challenges imposed on motors by outer space applications are immense, and making the false assumption that a commercial grade motor is an appropriate starting point will only expand the problem. As a NASCAR Team wouldn't use the motor of a Ford Escort as the building block for their Indianapolis 500 run, space researchers shouldn't use a standard commercial grade motor as the building block for space exploration. It may be a quality motor - it simply isn't right for the application at hand.

About the Author:

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Sidebar

Empire in Action

Wake Shield Satellite

The Wake Shield Satellite team was planning to position the satellite's solar panels using motors and gearboxes. Recognizing the technical challenges inherent in outer space applications, the design team turned to Empire Magnetics Inc. By selecting materials based on thermal characteristics and holding tighter mechanical tolerances, potential problems were avoided in three successful orbital missions. A fourth launch is planned, and to date, no motor or gearbox maintenance has been necessary.

Satellite Stabilization

Most commercial motors feature bearing holding plates constructed of porous cast aluminum which is machined. This aluminum holds air and other contaminants which can lead to outgassing problems. In addition, the aluminum has a different expansion coefficient from the steel or iron of the motor body. The differentials result in mechanical problems during thermal cycling.

Orbital Flight Systems needed assemblies for satellite inertial controls. Empire engineers constructed units of heavier material to improve mechanical stability and reliability. While the weight increase was contrary to the stated desires of the satellite designer, analysis demonstrated that a motor failure would lead to the failure of a multi-million dollar satellite system while in orbit. Faced with this responsibility the designer opted for reliability.

Space Station

Empire Magnetics has provided an array of motors, gearboxes, brakes and other components for the yet-to-be-launched Space Station. A number of servo motors are used to position the docking rings which move into position to match the craft - meaning the shuttle pilot no longer needs to adjust the position of the ship to +/- four inches. Once in location, another group of Empire motors and gearboxes latch and lock the mating rings together. In all, Empire has supplied 30+ units for both ground support and flight assemblies on the space station.

Brilliant Eyes

Many space craft designers are predisposed to selecting a motor sans housing. In their quest to reduce motor weight they select a mechanical design that is relatively unstable considering the reliability requirements of their application. They tend to compound the problem by selecting long, thin motors, which are less stable and reliable than shorter, thicker motors.

While working on the Brilliant Eyes program, Boeing, Corning OCA and Space System Group avoided these issues by accepting Empire's recommendation to design based on CYVX-U21and CYVX-U31 motor construction. These platforms have already addressed material and process issues, they are of the most reliable configuration, they have been mechanically stabilized and they have heavier housings. The Brilliant Eyes team has qualified the first set of motors in operation at 24 Kelvin and subjected to 25 G shock, qualifications were made without secondary rework or modification.