Establishing Adequate Performance Margin for Space Flight Stepper Motor Mechanisms

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Abstract

Adequate Stepper Motor performance margin is critical for mission success. Often, it is not clear from system specifications what the stepper motor performance requirements should be, because the concerns and methods for defining and applying a stepper motor may not be well understood. “Establishing Adequate Performance Margin for Space Flight Stepper Motor Mechanisms” presents practical guidelines for the correct specification and application of stepper motors used in space flight mechanisms and provides some basic lessons-learned from flight hardware experiences.

Introduction

System or mechanism specifications and the associated stepper motor specifications are typically different in terms of how the motor related characteristics are presented. It becomes important then for the stepper motor specifications to include a comprehensive definition of motor parameters to cover the system spec requirements but also those requirements derived and indirectly required to support the system motion control. In the system specifications, motor specifications, or within the motor supplier’s sizing of the design, the performance margin over and above the actual motor or mechanism output should be determined for stepper motors.

Unlike brushless DC motors, stepper motors cannot be relied upon to produce output torque as a function of input current. Motor speed, torque loading, and system dynamics affect the stepper motor’s ability to respond to input commands. Because stepper motors generally operate without feedback for commutation, velocity, or position (an advantage that simplifies the system and reduces cost), care must be taken to assure the stepper motor supplied can perform over the range of characteristics associated with the particular motion control system. Torque margin or voltage margin analyses must consider mechanism internal losses, external load and coupling variations, electrical tolerances, temperature change effects, viscous damping, and excitation pulse characteristics. The specification and sizing approach should evaluate minimum torque conditions, minimum stability conditions, system resonance, and minimum unpowered holding torque. Other considerations may apply, too, depending on the mechanical configuration, such as the maximum motor torque capability.

So, to compensate and account for inherent system variabilities and their influence on stepper motor-based mechanisms, adequate design margin must be built into the motor sizing. Established guidelines exist among users and manufacturers of stepper motors for quantifying margin requirements, but every application will hold unique concerns. Performance analysis using motion simulation tools is usually required to quantify the stepper mechanism performance over many varying conditions of operation. Heritage designs and their applications serve as a good reference and should be consulted along with analysis and simulation, but ultimately hardware testing will demonstrate the success of the stepper motor mechanism.

The motor specifications, analysis assumptions, and hardware testing should agree in methodology as closely as possible. Otherwise, the design and test approach will be flawed. It is possible to provide a well designed and tested stepper motor or stepper mechanism that does not meet the system requirements if the methodology used does not relate well to how the mechanism will actually be used. Or, specification requirements that are too severe can penalize the program with unnecessary weight, costs and delays. It

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is important to have an understanding of stepper performance specification development, performance margin and methodology, stepper simulation and analysis, stepper hardware testing, and past lessons learned.

Lessons learned from stepper motor usage on space mechanisms can be categorized into four different areas that will be explained further. These Lessons Learned areas are: torque production assumptions, temperature effects, under-margin and over-margin, and electrical input effects on step stability. Critical motor application errors can be avoided if these areas of concern are consistently addressed.

Background

A two-axis stepper motor / harmonic drive rotary actuator typically applied in such applications as antenna pointing mechanisms is shown in Figure 1. Margin on stepper motor requirements is required, because unlike similar brushless dc motors, the stepper motor runs in an open loop mode without any feedback to regulate its commutation or rotation other than the motor input pulses.

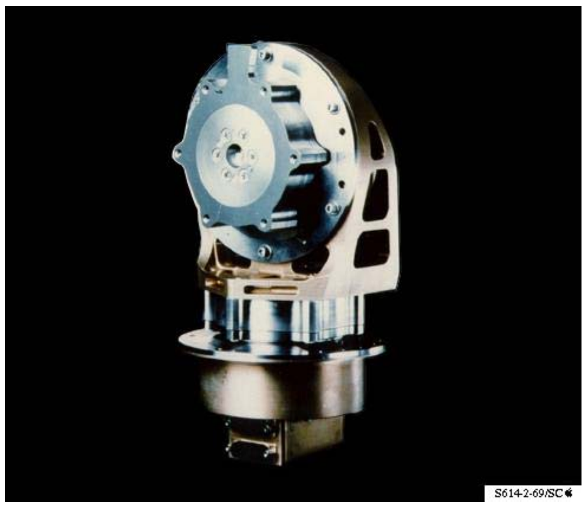

Figure 1. Stepper Motors with Harmonic Drives for a Two-Axis Antenna Pointing Mechanism

It is necessary in applying a stepper motor to carefully define ranges (minimums or maximums) on many parameters, such as the motor speed (pulse rate) to assure that the motor and load rotation remain synchronous over all conditions of voltage variation, temperature and internal frictional drag changes, load variations, etc. Synchronous operation is the precise electro-mechanical interaction required between the motor controller, stepper motor, and output load so that every discrete motor rotation (step) that is commanded results in the proper and precise incremental rotation of the load. This is accomplished without any position feedback devices for control (other than perhaps an end of travel sensor or potentiometer.) Electrical pulses are sequenced, counted, and supplied to the motor. Multiplying the known motor step angle by the pulse count determines the angular rotation of the motor output, if the system remains synchronous. The corresponding angle of the load rotation is related by any gear reduction that is present between the motor and the load.

Since the stepper motor does not operate in a closed, servo loop mode of operation (which results in a simpler, less expensive operating system), the effective torque production varies according to a number of factors, and so the traditional dc motor method of determining torque as presented in Equation 1.0 does NOT apply:

$$T_{ouput} = (Kt \times I) - T_{loss} \quad (1)$$

Where,
T_{ouput} is the net output torque of the motor
Kt is the motor torque sensitivity constant, torque output per amp input

I is the motor input current
T_{loss} is the sum of all internal motor, bearing, drag, etc. torques.

The stepper motor torque cannot be calculated simply based on Kt as with brushless motors, so margin to compensate for this must be imposed in the performance analysis. Margin factors for stepper motors are used to either increase the torque requirement (internal and external) or to reduce the available voltage. It is common to apply established margin factors to the internal and external load requirements to arrive at a set of speed and torque conditions that the proposed stepper design must meet (typically by analysis). If the performance analyses cannot show the design will comply, then it is deemed to have insufficient margin to assure satisfactory test and flight operation. The margin factors used are typically those established by the company designing the system or the motor manufacturer supplying the motor design and will vary somewhat.

The process of deriving motor requirements from system or mechanism performance requirements and of imposing sufficient margin for the particular mechanism application is essential to proper stepper motor sizing. A comprehensive stepper motor specification must include an approach that correlates the specifications, simulation and analysis, and hardware testing. The motor specification approach outlined in Table 1 is suitable for guiding this process. However, it will need to be tailored to the specific application and technical requirements. Table 1 is applications oriented, directed towards the systems or mechanism designer desiring to utilize a stepper for a space flight mechanism. Typically, the systems or mechanism engineer will require assistance in working through the detailed level of evaluation and simulation normally required for stepper motors in space applications.

Table 1. Guidelines for the Stepper Motor Specification Process

	DEFINITIONS	*LIMITATIONS*	*CORRELATION*
(1.a) Translate System and Mechanism Specs into Stepper Motor Requirements ↓	Key Derived Ratings: Speed (Pulse Rates) Load Torques Inertial Loads Step Angle and Output Resolution (Trade-off Analyses)	Key System Limitations: Unpowered Holding Maximum Output Torque Pulse Width Input Power Driver Circuitry Scheme Hard-stops	Margin Approach: Heritage Review Torque Margin Voltage Margin Combination [Ref. Table 3]
(1.b) Evaluate and Iterate Motor to Meet Requirements ↓	Key Motor Parameters: Kt and DCR Ranges Detent Torque Range Pull-in and Out Torques Rate Capability Viscous Damping Rotor Inertia	Thermal Limitations: Duty Time-On Ambient Range Winding Temp. Rise Cold Start Drag Torque Installation Mounting Thermal Mass	Analysis and Test: Test to Spec with Margin only in Analysis…or Include Margin at Testing
(1.c) Simulate Dynamic Performance and Confirm with Hardware Testing	Dynamic Models: Assess capability of motor to meet specs, margin, and duty	Worst Case Limitations: Environmental Extremes Electrical Combinations Mechanical Combinations	Test Confirmation: • Motor Only • Mechanism • System

Translating System and Mechanism Specs into Motor Requirements

Translating system and mechanism specs into specific motor requirements is highlighted in Table 1, section (1.a), and broken up into three parts: Definitions – Key Derived Ratings, Key System Limitations, and Correlation – Margin Approach. Failure to address any of these three areas during development of the stepper motor specifications will result in performance difficulties or failures later on in the project. Following this process is (1.b), Evaluation and Iteration of the stepper motor to meet the requirements developed in (1.a). Developing the specifications in (1.a) will depend significantly on trade-offs associated with the selection of the mechanical reduction (planetary gears or harmonic drives typically.) Because stepper motors are fixed angle, speed sensitive, and torque limited, a careful trade between reduction ratios and motor performance is necessary.

It should be understood that stepper motors come in specific packages that tend to restrict the step angle size as a function of diameter. A large angle stepper will usually come in a small diameter package. Conversely, a small angle step motor usually comes in a larger diameter package. Table 2 indicates for reference step motor angles and corresponding motor diameters. Note that the step angle is also dependent on the number of motor phases. There is a style of industry stepper referred to as “Hybrid” that possesses a small step angle (1.8 degrees) in a comparatively smaller diameter and so is “out-of-family” with the typical diameter versus step angle size shown in Table 2. This difference makes the Hybrid 1.8 degree stepper popular for some applications.

Table 2. Motor Step Angle and Typical Diameter Relationships

Step Angle (Degrees)	Diameter Range (mm)	No. Winding Phases
90.0	27.1 – 63.5	2 / 4
45.0	27.1 – 44.6	2 / 4
15.0	27.1 – 63.5	2
3.75	50.8 – 140	3
2.0	117	2
1.8 *	38 – 86.4	2 / 4
1.5	99 – 117	3

*1.8 degree stepper shown is of special Hybrid configuration.

A stepper motor having a 2.0-degree step angle would need to be pulsed at a rate of 180 pulses per second (pps) to achieve one revolution in one second (2.0 deg x 180 pps = 360 degrees of rotation per second). By comparison, a 90-degree stepper motor could go through one revolution with only a 4 pps excitation rate (90 deg x 4 pps = 360 degrees of rotation per second.) So, the larger step angle motors can operate at slower rates but achieve greater speeds. But, actuator resolution is also affected by the step motor angle chosen, and the 2.0-degree stepper will have 45 times smaller angular resolution than the 90-degree stepper. Hence, clear trade-offs exist between actuator resolution, motor pulse rate, and motor torque. While there are exceptions, most space-rated stepper motors are specified to operate with a maximum rate between 200 and 1000 pulses per second, depending on the size and voltage input.

Because changes in gear reduction affect the motor operation rates, usually a trade exercise occurs to determine the optimum torque and speed maximums within the capability of the motor. Stepper motors are uniquely sensitive to speed and torque ranges and do not have a linear speed-torque curve. A single axis stepper motor harmonic drive unit like shown in Figure 2 is bounded by a maximum no-load speed range or pulse rate and a maximum powered holding torque (comparable with “stall torque.”) This is similar to a brushless dc motor, but due to the absence of commutation control, the performance curve between no-load speed and stall torque is non-linear, may have “drop-out regions”, and may even differ for every application. The best first approach is to identify stepper motors and manufacturer's data that are comparable with the new application, either through knowledge of steppers that have been used before or through manufacturer's catalog data. Then, narrow the selection of motor models based on further trades and analyses.

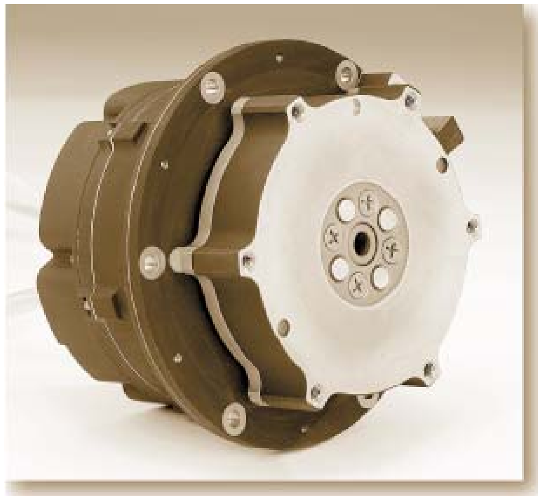

Figure 2. Single Axis Stepper Harmonic Drive Unit

Load torque is essential information for developing initial stepper motor specifications, but it must be understood that selecting a stepper from catalog data based on load torque requirements will not yield satisfactory results. Typically, catalog data is provided for operation a room temperature and has little if any margin applied to assure that performance goals will be met in a space application. It becomes important, then to also know the full range of the mechanism's loading over temperature and other extremes and the amount of margin that is deemed sufficient. From the stepper motor's perspective, the internal drag associated with its bearings under cold start-up conditions can be as significant as the external load reflected through the gear reduction. Hence, step motor specifications must attempt to address the range of external loads, internal loads, and the extent of torque margin required before a motor can be sized.

Another torque characteristic typically needed with stepper motor applications is called "unpowered holding torque." This property is the result of magnetic detent within the motor that causes it to hold its position when no power is applied. A certain amount of detent is necessary to assure that when step excitation has ceased the motor rotor position rests at the expected location. This may not be true if external dynamic effects are sufficient to overcome the unpowered holding torque. Unpowered holding torque is commonly used within space mechanisms to hold the mechanism position against rotation once power is removed from the motor.

If a minimum amount of unpowered holding torque is present within the motor design, then a minimum amount of mechanism holding can be expected. So, it is common for the mechanism and hence motor to have an unpowered holding torque specification. It should also be noted that too much motor detent torque can interfere with meeting dynamic torque requirements, so it may be necessary to have both a minimum and maximum holding torque spec (commonly defined through the motor's detent).

Unlike brushless dc servomotors, which have varying power inputs depending on the changing load requirements, stepper motors operate on a constant level of power input. This at first may seem surprising, but once it is realized that the stepper actuates based on series of electrical pulses, the power situation becomes better understood. The full level of power is applied at every motor step regardless of the loading situation. Since the power input is essentially at maximum for every step, an assessment of the duty cycle, average power input, and motor thermal capability becomes very important. A motor may be chosen that meets step resolution and the speed – torque requirements but be found to have insufficient size and thermal capacity. The motor mounting characteristics should be included if possible in the specifications.

As a consequence of full power being applied at every step of a stepper motor during its operation, schemes have been developed to reduce the average applied power. A common stepper driver feature that accomplishes this is the practice of restricting the “on-time” of an electrical step pulse to only a fraction of its theoretical maximum duration. This practice of operating with a reduced or “partial pulse width” may reduce average motor power consumption and internal motor heating, but it can also affect motor stepping capability. If a partial pulse width is intended for operation, this needs to be indicated early on. Besides the possibility of operating with a partial pulse width, it is also common to have a current limit applied. Because the driver design can play a critical role in the operation of a stepper motor, it is important to have the intended drive electronics and its features defined.

Once the motor specifications have been derived from system level requirements, drive requirements, and trade-offs to arrive at optimum rates and torques, the issue of performance margin for the mechanism must also be addressed. Performance margin may be addressed as margin on torque, voltage, or losses. Performance margin for space mechanisms can be defined through use of several methods that are sometimes used together as summarized in Table 3. It should be noted that margin can be applied twice or more through the specification process, sometimes unintentionally, resulting in hardware that is over-sized.

Generally, the hardware should be designed to meet several times the actual performance requirement (as determined by the margin), and then tested to meet the actual requirement over worst-case conditions. If hardware must be tested at several times the actual requirement, then the motor must be sized with additional factors that may unnecessarily increase motor weight and volume. Table 3 assumes that margin is only applied one time for purposes of meeting the specified requirements derived from the actual mechanism demands. While the Table 3 methods are commonly known, it is hoped that clarification and possibly standardization of their use will result.

Table 3 provides guidelines that the system or mechanism level designer can use to specify margin for space stepper motors, so that when the design is created and analyzed sufficient design margin will be present to assure actual torques and speeds are met over all the worst-case conditions at test. It is important that the specifications be clear as to whether the margin applies for design analysis purposes only or if factors shall be applied at test as well. Sometimes it is desired that the requirements for test be set beyond the actual needed values by some margin factor. If this course is chosen, the system or mechanism level engineer must realize that the stepper motor will be sized accordingly with some additional size and weight penalty.

Torque load and internal loss margin factors can vary, because applications are different. Stepper motor designers also vary in their conservatism. The actual factors to apply should rest in a mutual agreement between system, mechanism, and stepper motor design engineers for their specific project but based on successful heritage margin values. In general, it is not uncommon to see load and loss torques increased by factors of several times to assure steppers will function as desired (reference Table 3.a). The same is nearly true of taking voltage reductions, although these generally must be applied more thoughtfully, since voltage affects both speed and torque (reference Table 3.b)

Heritage data (reference Table 3.c) may provide a reference of acceptable margins from test history but may not be as clear regarding the actual design margin used if the hardware is from a very mature program. So, heritage data should be taken as reference if older or intended margins are unclear, and then combined with one of the other methods of margin. It is of great importance that the margin methodology agrees from specification to analysis to test.

Table 3. Specifying Margin in Stepper Motor Performance

Specifying Margin in Stepper Motor Performance	Specification	Analysis	Test
(3.a) Apply Factors to Loads and Losses during analysis to assure actual requirements are met in test	States specific load and loss torques with factors that should be applied during analysis but not in hardware test	Use torque values that include the margin factors and simulate to show compliance	Test at the required torque values under worst case conditions but with no factors applied
(3.b) Reduce Applied Voltage during analyses; but test with normal voltage	Specify a reduced applied voltage that reflects desired margin for analysis purposes only	Use reduced voltage for simulating operation and specific performance points	Test using the normal voltage to meet specified performance
(3.c) Use Heritage Mechanism Data to Qualify Similar New Designs	Reference the Heritage specifications	Reference the Heritage analyses and make minor modifications as needed	Test similarly to the heritage mechanism

The application of margin factors to load and loss torques may take on another form besides that shown in Table 3, the torque margin being derived from an equation relating measured to required values. For example, a measured maximum output torque value under worst case conditions would be divided by an expected torque loss value (sometimes measured also) to arrive at a margin factor above internal losses. Additional torque loading may be added to represent an output load or may be factored into the margin equation.

This approach is not uncommon but tends to compound the margin within a stepper motor application. The reason for this is that when margin factors within a specification must be demonstrated at test by a calculation based on measured torques, the analysis component of the process must contain “additional padding” so that margin over the tested amounts is present. A stepper’s response is not linear or predictable like that of a brushless design. In order for a stepper to produce, for example, three times more torque output than the requirement, the sizing of the motor must go some factor beyond that in order to actually test out a margin factor of three. Hence, the motor design might need to incorporate a factor of five over expected torques, for example, in order to test out a factor of three times the torque requirement. So, the specification of torques and application of margin must be thought through very well and correlated with the analysis and test approach to achieve a reasonable outcome.

Evaluation, Simulation, and Testing of the Stepper Motor

Preliminary evaluation of the stepper motor performance comes through a review of its catalog or historic use data. This involves looking at the available torque production capability, and realizing that the rated value of torque will need to be de-rated in accordance with the margin factors chosen. Speed maximums should also be reviewed with a close look at the motor step angle and number of motor phases. The peak and continuous output data (if available) must always be judged relative to the conditions associated with the rating. Typically, space environments offer the least favorable conditions from a thermal standpoint. Tolerances on the motor winding constants, magnetic detent, voltage, current, temperature extremes, etc.

must be considered to begin developing a complete analysis of the performance. Additionally, mechanical characteristics such as coupling stiffness, bearing drag losses, motor and load inertias, etc. must also become a part of the performance simulations.

While most of these parameters are readily available from the system description, motor catalog specifications, and historical references, it is essential that the performance analyses include these over the full range of operating conditions. While it is beyond the scope of this paper to address how to accomplish a stepper motor and mechanism performance analysis, the preparation for doing such is well known. So, it is worthwhile to at least recognize the basic performance analysis parameters as part of establishing adequate performance margin for steppers:

- Motor step angle
- Motor number of phases and winding type
- Motor torque sensitivity, Kt, with tolerances
- Motor winding resistance with tolerances and effects of thermal rise
- Motor inductance with tolerances
- Motor mounting, heat dissipation, and thermal rise model
- Motor rotor inertia
- Number of motor poles
- Minimum and maximum motor detent torque
- Supply voltage and tolerances
- Supply current maximum and any pulse width restrictions
- Environmental temperature range
- Temperature range effects on bearing drag torques
- Load drag torque, load inertia, and coupling stiffness
- Operating profile and duty cycle
- Gear reduction characteristics.

Failure to consider the worst-case extremes of these parameters will result in improper performance assessment and operating anomalies. It should be well understood but is worth mentioning that in stepper mechanisms the performance analyses may detect areas of concern not related to meeting the margin goals but related to dynamic stability at certain speeds, commonly resonances. Hence, it is impossible to develop a thorough stepper motor mechanism performance analysis based solely on static estimates associated with margin. In fact, a well-established method for simulating the stepper mechanism motion over a broad range of operation conditions is essential. Commercially available and custom software are used for accomplishing the motor and system level performance simulations.

Performance simulation is best done using methodologies that have been successful in the past in correlating with test results. Sometimes it is difficult to replicate the stepper mechanism in its precise flight configuration, because of model and / or test set-up limitations. So, it is important first of all to realize what the modeling and test deficiencies are and secondly to make sure that the performance modeling and lab testing are intended to correlate well. Correlation must be present between performance modeling and lab tests. Often it is easer for the performance simulation to replicate the flight configuration than it is for the test set-up. This can occur when the flight configuration involves large masts or solar panels. If the performance modeling accurately simulates the flight configuration but not the test lab configuration, then anomalies in test can occur that reflect test set-up deficiencies rather than potential flight problems.

Hardware testing should consist of tests at every level of the system, from the stepper motor components to the mechanism assembly. Of primary importance is identifying the specific tests and limits that will best represent the actual flight conditions and then assuring that the design, simulations, and testing follow consistently. Testing at the motor component level looks at the parameters that determine torque, speed, power, angular movement, and positional stability. Testing at the mechanism level looks at torque output and margin, rate and resolution, and step stability. Testing for both the motor and mechanism should incorporate environmental factors, especially temperature extremes. It is very desirable to use flight-like drive electronics for testing. Table 4 summarizes the types of testing generally performed on stepper motors and mechanisms and how these should follow from specification and analysis strategies.

Table 4. Basic Stepper / Mechanism Testing for Correlation with Specifications and Analyses

Specification Parameter	Analysis Correlation	Motor Component Test	Mechanism Test
Electrical Characterization	Estimate motor Kt, R_{ph}, and L_{ph}	Verify electrical parameters	(Usually only minimal electrical verification)
Output Resolution	Define Step Angle	Step Accuracy Test if applicable	Output Resolution
Unpowered Holding Torque	Estimate Minimum Detent and Bearing Drag	Motor – measure detent Bearings – measure drag over temperature	Measure unpowered holding torque over temperature
Powered Holding Torque	Motor gross output torque less internal losses must provide margin over loads; simulate with margin on losses and loads	Measure net output torque and internal losses; adjust analyses and simulation models for any loss variations	Measure powered output over temperature to confirm PHT spec is met (no margin applied)
Specific Torque and Rate Operation (using driver pulse width, current limit, etc.)	Optimum gear reduction with motor rate and torque, simulate over worst cases with flight driver limits	Dyno test motor and include margin on losses over worst case thermal concerns; use flight-like driver	Test output rate and torque at worse case w/ flight driver. Can test above rate and torque spec for reference.
Dynamic Performance (New stepper motor characterization should go beyond mechanism requirements)	Predict & analyze pull-in and pull-out torque performance and if electronic rate ramp is needed for operation	Especially for new designs, perform pull-in and pull-out torque characterization; evaluate rate ramp	Verify mechanism performance over dynamic ranges required and all worst case conditions

The margin approach used in Table 4 is the same as used in Table 3, which does not compound the margin factors. However, if the margin must be demonstrated during test beyond that actually needed to meet the specification, then the additional margin must be built into the analyses and motor testing as well. Some test anomalies are the result of not following the same margin strategy through from spec to test.

Lessons Learned in Establishing Adequate Performance Margin

Proper sizing with thorough analysis and test will usually address most stepper motor applications concerns. However, there are some problem scenarios that should be identified in a lessons learned format. These are largely from historical lessons and should be considered relevant when establishing performance margin in a stepper mechanism. Lessons learned from stepper motor usage on space mechanisms can be categorized into four different areas:

- Torque Production Assumptions
- Temperature Effects
- Over / Under Margin Use
- Electrical Driver Features / Differences.

Incorrect Torque Production Assumptions

Incorrect torque production assumptions can be made during the motor selection and sizing phase due to the casual usage of the motor Kt. In a stepper motor, the Kt is a reference figure used in helping to determine the winding scaling and in comparing motor capabilities, along with the motor constant, Km. But, if the Kt is multiplied by the current to obtain a "torque estimate" without recognizing the open-loop operation characteristics of the stepper and without any margin considerations, then the motor sizing will be very lacking in torque capability. This concept is at the heart of establishing adequate performance margin, because Kt and Kb by themselves cannot be used to predict what the speed-torque output will be.

Unanticipated Temperature Effects

Unanticipated temperature effects can have a great impact. The first concern is attempting to size a motor working only with the ambient temperature resistance. The hot ambient temperature can be used to easily calculate the change in winding resistance from nominal to hot conditions. But of equal or greater importance, is the potential for thermal rise due to internal motor heating. This is much more difficult to address than the effects of a hot ambient temperature. The mounting conditions and thermal transfer from the motor into its flight mounting may not be well defined; this in combination with an uncertain duty cycle can create uncertainties in the winding temperature. Elevated winding temperatures, which may be within the rating of the motor materials, can exceed that expected in the performance model. And, so the expected performance can suffer.

Inadequate or Inappropriate Uses of Margin

Inadequate or inappropriate uses of margin either by the torque or voltage method is sure to cause performance deficiencies. Because stepper motors are different in design and their applications also vary considerably, there is some understanding that torque margin factors may vary within a reasonable range. As these factors are applied over a history of programs, a basis for establishing the necessary ranges of factor values is developed. To the extent that performance simulation tools increase in accuracy of prediction, the factors may be reduced a bit. Fundamentally, the stepper motor's output is very dependent upon the dynamics of the system. And, so to evaluate a stepper motor independently of the system in which it will be used is not acceptable. Hence, the need is present to incorporate torque margin factors from a well-known range to help assure that performance goals will be met.

It should also be understood that the inclusion of such margin factors does not guarantee that performance will be satisfactory under every condition, because other influential conditions may exist such as system resonances. In fact, some conditions of the worst-case system analysis are not correctly simulated if the torque margin is applied to the loads and losses. These simulations that evaluate the motor and system stability are better served if the margin factors are omitted and losses are reduced closer to the minimum values. Closely related to this type of concern is speed dependent damping associated with the motor magnetic properties and the electronic drive circuitry.

In a broader sense, to cover the full perspective of performance margin, it is necessary to evaluate not just the torque requirements and associated margin factors but also the dynamic stability of the motor in its system. While this is certainly understood by system and mechanism designers, for the sake of presenting a complete perspective of stepper motor performance it is mentioned. In addition to the conditions of operation where factors are applied and those conditions where they are not, other unique conditions should also be considered. For example, if there is the possibility of the mechanism encountering hard-stops, then the requirements outlined in harmonic drive catalogs for ratcheting torque must be observed. Restrictions may be required to prevent the over-production of motor torque, that is, the maximum motor torque possible should not reach or exceed a percentage of the maximum harmonic drive ratcheting torque rating. Otherwise, damage to the harmonic drive could result. This additional aspect and others like it associated with unique system design concerns must be addressed as well as the obvious performance margin concerns.

The Electronic Driver

The electronic driver for the stepper motor can have as significant an effect on performance as the system dynamics. Excluding the obvious factors of available voltage and current, other driver parameters if overlooked can impair the resulting system performance. Probably the most significant driver parameter to be concerned about is the use of a partial pulse width. As already explained, this is implemented to help reduce the average power consumption of the motor. But, if the partial pulse width feature is overlooked in the motor design analysis, then the performance can suffer at lower speed ranges where it takes effect. Specifications must be clear about this feature, and performance simulations must take its use into account. A similar and more obvious feature is the current limit.

In some systems, a stepper may be required to start at a rate that exceeds its capability. So, an electronic rate ramp can be part of the drive electronics to start the motor at a workable speed and quickly advance to the higher rate. This type scheme is typically not proposed in a driver but is the result of the motor and system performance analyses, which may show that such a feature is required. If the performance analyses fail to uncover this concern, then it will surely be uncovered during testing.

A more common problem that occurs is the result of using commercial drive electronics for motor components testing that usually differs in design from the space flight drive electronics. This can introduce minor performance differences or major ones, depending on the electronics. In many cases the flight drive electronics are not available for use with the motor components, but a reasonable compromise is to build a commercial grade drive box based on the flight electronics schematic.

Summary and Conclusions

Adequate stepper motor performance margin is critical for mission success. System or mechanism specifications and the associated stepper motor specifications are typically different in terms of how the motor related characteristics are presented. Unlike brushless DC motors, stepper motors cannot be relied upon to produce output torque as a function of input current. Motor speed, torque loading, and system dynamics affect the stepper motor's ability to respond to input commands. To compensate and account for inherent motor and system variabilities and their influence on stepper motor-based mechanisms, adequate design margin must be built into the motor sizing. The motor specifications, analysis assumptions, and hardware testing should agree in methodology as closely as possible.

It is necessary in applying a stepper motor to carefully define ranges (minimums or maximums) on many parameters, such as the motor speed (pulse rate) to assure that the motor and load rotation remain synchronous over all conditions of voltage variation, temperature and internal frictional drag changes, load variations, etc. The process of deriving motor requirements from system or mechanism performance requirements and of imposing sufficient margin for the particular mechanism application is essential to proper stepper motor sizing. A comprehensive stepper motor specification must include an approach that correlates the specifications, simulation and analysis, and hardware testing. Table 1 is applications oriented, directed towards the systems or mechanism designer desiring to utilize a stepper for a space flight mechanism, and provides guidelines on specifying and correlating stepper motor requirements for motor specification, analyses, and testing.

Preliminary evaluation of the stepper motor performance comes through a review of its catalog or historic use data. While most of the relevant parameters are readily available from the system description, motor catalog specifications, and historical references, it is essential that the performance analyses include these over the full range of operating conditions. Failure to consider the worst-case extremes of these parameters will result in improper performance assessment and operating anomalies. Performance simulation is best done using methodologies that have been successful in the past in correlating with test results. Correlation must also be present between performance modeling and lab tests. Testing at the motor component level looks at the parameters that determine torque, speed, power, angular movement, and positional stability. Testing at the mechanism level looks at torque output and margin, rate and resolution, and step stability.

Inadequate or inappropriate uses of margin either by the torque or voltage method is sure to cause performance deficiencies. It should also be understood that the inclusion of such margin factors does not guarantee that performance will be satisfactory under every condition, because other influential conditions may exist. In a broader sense, to cover the full perspective of performance margin, it is necessary to evaluate not just the torque requirements and associated margin factors but also the dynamic stability of the motor in its system. Table 3 provides guidelines that the system or mechanism level designer can use to specify margin for space stepper motors, so that when the design is created and analyzed sufficient design margin will be present to help assure actual torques and speeds are met over all the worst case conditions at test. It is important that the specifications be clear as to whether the margin applies for design analysis purposes only or if factors shall be applied at test as well.

Stepper motors have been an important motor type for use in space applications offering advantages over brushless and brushed motors in many applications. It remains relevant that those who design stepper motor based mechanisms and are involved in developing specifications for stepper motors understand their application concerns. This is truer with steppers than brushless and brushed motors, because steppers tend to change their individual performance characteristics from one system to another. Establishing adequate performance margin is therefore a critical process and should be carefully explored as new applications emerge for stepper motors in space flight.