ELECTRIC MOTOR DESIGNS FOR ATTENUATING
TORQUE DISTURBANCE IN SENSITIVE SPACE MECHANISMS

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Abstract

When a motion control system introduces unwanted torque jitter and motion anomalies into sensitive space flight optical or positioning mechanisms, the pointing accuracy, positioning capability, or scanning resolution of the mission suffers. Special motion control technology must be employed to provide attenuation of the harmful torque disturbances. Brushless DC (BLDC) Motors with low torque disturbance characteristics have been successfully used on such notable missions as the Hubble Space Telescope when conventional approaches to motor design would not work. Motor designs for low disturbance mechanisms can include two and three phase sinusoidal BLDC motors, BLDC motors without iron teeth, and sometimes skewed or non-integral slot designs for motors commutated with Hall effect devices. The principal components of motor torque disturbance, successful BLDC motor designs for attenuating disturbances, and design trade-offs for optimum performance are examined.

Introduction

The type of BLDC motor and drive system chosen must match the overall mechanism requirements well in order to assure a successful, low disturbance design. Torque disturbances are a concern in sensitive space flight applications, because they can introduce pointing jitter, positional error, and unwanted motion in a satellite structure. Torque disturbances from BLDC motors come from two principal sources: motor magnetic cogging and torque ripple. Magnetic cogging is a function of the pole magnet's interaction with motor slot teeth and exists whether power is applied to the motor or not. The system torque ripple is affected by the motor design, electronic driver, and commutation scheme chosen.

In order to tailor a brushless dc motor design to meet low disturbance requirements, key motor parameters are affected. So, a conscientious tradeoff between motor constant, torque output, power, and torque disturbance is required. A close collaboration of the satellite system designers and motor / driver designers is usually required to achieve the optimum drive system with an acceptable level of torque disturbance.

Both of the key components of motor torque disturbance, magnetic cogging and output torque ripple, can be predicted analytically and tested for compliance. Analysis methods are complex, requiring optimization of the design for both cogging and torque ripple. Motor magnetic cogging can be tested through evaluation of the motor detent torque when plotted at slow motor speeds. Output torque ripple can be evaluated by testing the harmonic content of the back emf voltage, determined through spectral analysis.

The BLDC motor shown in Figure 1.0 is used for acquisition and fine pointing functions in the Hubble Space Telescope. This unit is a two-phase BLDC motor designed and subsequently tested for low levels of disturbance torque. Cogging was measured at less than 7.1 millinewton meters (1.0 oz.in) and torque ripple was evaluated at less than 0.20%. This is remarkable considering that the Stator OD is 22.9 cm (9.0 inches.) The motor constant is 424 millinewton meters per square root watt (60.0 oz.in per square root watt.)

Figure 1.0 – BLDC Low Disturbance Motor used on Hubble Space Telescope (Photo - Courtesy of Moog, Inc.)

Once the components of motor torque disturbance are understood, then there are several motor and system design approaches that can be applied to minimize disturbance. The approach selected must be determined through a careful trade-off with the performance requirements. Most of the features implemented in the motor design that attenuate disturbances also reduce the torque output capability for each watt of power input. It is important for the system designers to correctly identify the level of disturbance required, because being too conservative will change the motor approach and reduce torque output per square root watt (Km). Table 1.0 highlights the motor design options for various levels of torque disturbance and the basic trade-offs.

Proper application of low disturbance brushless designs will help meet system level disturbance and noise requirements. It is important for system designers to understand the implications of the driver and commutation schemes they select because of the direct impact upon the type of motor than can be used. An informed brushless DC motor selection will help assure that overall satellite mechanism jitter, position, and accuracy requirements are met.

Torque Disturbance Components

The principal components of BLDC motor torque disturbance are motor magnetic cogging and torque ripple. Motor magnetic cogging is the result of pole magnet faces seeking to align with the slot teeth in a stable or minimum energy position. Unless a motor does not have slots and teeth, the cogging effect is always present and superimposes onto the torque ripple the motor produces. The cogging effect is generally only seen at slow rates of motor rotation and diminishes as speed increases. So, slow speed applications are especially susceptible to cogging effects.

Cogging can be measured and plotted (motor is unpowered) as shown in Figure 2.0. Normally, cogging is taken as the zero to peak value, so the peak-to-peak measurement of adjacent positive and negative peaks is divided by two to obtain the magnetic cogging. In Figure 2.0, the cogging is about 60.0 millinewton meters (8.5 oz.in.)

Sensitive mechanisms operating at slow speeds are not tolerant of torque disturbances and require cogging to be very low. Cogging is reduced either through the type of motor design chosen, perhaps with stack skewing, or through the use of a larger air gap. All of these options reduce the motor's capability to produce output torque within a given volume and power. Hence, there is a trade-off required to optimize magnetic cogging and motor size. A similar trade exists for the attenuation of output torque ripple.

The torque ripple content present in motor output torque is very closely related to the motor back emf voltage. Especially in sinusoidal BLDC motor systems, the output torque ripple is determined by evaluating the

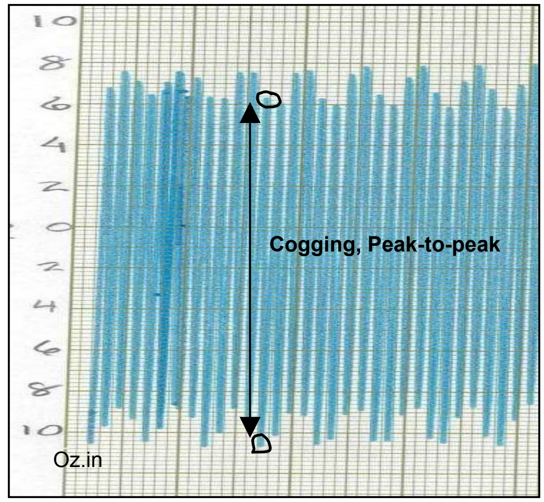

Figure 2.0 – Motor Magnetic Cogging

amount of non-sinusoidal content (harmonics) in the back emf voltage. Assessment of the back emf harmonic content then gives a direct correlation with the actual torque output ripple, except that the effects of the electronics drive circuitry are not included. Torque disturbance reduction is accomplished through attenuation of individual harmonics.

Figure 3.0 is a sample of a motor's back emf after harmonic analysis from a spectrum analyzer. The fundamental is prominently shown on the far left. The third, fifth, seventh, and ninth harmonics are shown to the right of the fundamental. Since a log scale is used, the harmonic content is less than one percent of the fundamental based on an evaluation of the harmonics individually.

Complex design analyses can predict the magnetic cogging and torque ripple harmonics in advance of testing. The testing performed on a motor similar to that shown in Figures 2.0 and 3.0 will provide confirmation that the requirements for the individual torque disturbance components have been met.

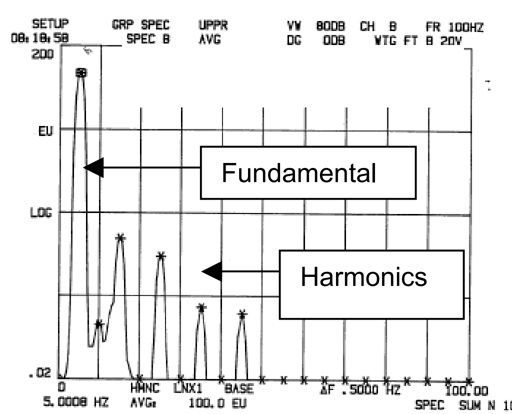

Figure 3.0 – Back EMF Harmonic Content

BLDC Motor Designs for Low Torque Disturbance

Successful brushless motor design approaches for attenuating torque disturbances include two and three phase sinusoidal BLDC motors, BLDC motors without iron teeth, and sometimes skewed or non-integral slot designs for motors commutated with Hall effect devices. Depending on the trade priorities for the system, each of these design categories offers advantages. The primary performance parameter traded against low torque disturbance is the motor constant, Km, which is defined as stall torque (Ts) per square root watt (Ps) in Eq. 1.0. This is used as a figure of merit in evaluating a motor's performance against other factors like weight and size. Low torque disturbance motors have a lower Km than comparable designs with standard ripple and cogging.

Eq. 1.0
$$K_m = \frac{T_s}{\sqrt{P_s}} = \frac{K_T}{\sqrt{R}}$$

Two and three phase sinusoidal brushless motors require a sinusoidal current input with resolver feedback (typically). When properly designed, this motor type offers the lowest torque ripple, even lower than that of motors without iron teeth, because the slot and winding design can provide harmonic attenuation. The pole design can be such that motor cogging is kept to a minimum. The result of extremely low motor torque ripple, less than one half percent in some cases, and very low cogging, together usually offer the lowest torque disturbance system.

Another category of brushless motor uses a winding without slots or magnetically permeable teeth. This "toothless" design has the distinct advantage of zero cogging and a sinusoidal back emf. If a sinusoidal driver is used, then there is potential for a very low torque disturbance system, but at the expense of torque output and Km. The large air gap required to accommodate the motor windings without a magnetic tooth structure keeps motor output for its size, weight, and power below that of steel slotted motors. Typically, the toothless design is three phase and excited by a six-step trapezoidal driver for lower cost. The benefits of this type motor for low torque disturbance cannot be realized with the less expensive six-step driver approach, however. To achieve matching of the back emf waveforms between the motor and the driver, a sinusoidal driver and resolver should be used for lowest torque ripple.

When considering the type of low disturbance system to use, the motor, driver, and commutation scheme must be analyzed together. For optimum performance, the two and three phase sinusoidal brushless motors must be operated with a sinusoidal driver and resolver (or equivalent) feedback device. If the sinusoidal motor is mixed with a trapezoidal output amplifier, then the system will have higher torque ripple. Similarly, a trapezoidal back emf motor should be used with a conventional six-step trapezoidal driver, but the trapezoidal system approach trades lower cost and less complexity for a higher level of torque disturbance. Special steps must be taken to address the torque ripple and cogging when a trapezoidal six-step system is chosen.

A trapezoidal motor and drive system is often chosen for lower torque disturbance when lower cost, less complexity, and a higher torque output (higher Km) are also concerns. The use of Hall Effect devices for commutating the six-step type system means that the motor back emf must be kept fairly trapezoidal for low ripple. This is hard to accomplish along with low cogging. Motor designs that include skewing or non-integral slot-per-pole approaches may be used, but more care in design and fabrication will be required to produce hardware with lower disturbance than a typical six-step system offers.

Design Trade-offs

The torque disturbance ratings shown in Table 1.0 are dependent on a number of factors including the specifics of the application such as rotation speed. The type of drive electronics and the commutation method are also key components contributing to the torque disturbance. Generally, the better the driver output current waveform matches the motor back emf, the less the torque ripple will be. Sinusoidal motors are very compatible with low cogging requirements, because a motor design providing a sinusoidal back emf waveform has lower cogging without a penalty, except for some reduction in the motor constant, Km.

The most common trade concern is meeting the necessary low torque ripple and low cogging but also achieving a high motor Km requirement. This is the most common challenge, because the low torque disturbance features of the motor design reduce motor output capability. Low disturbance features that erode Km include a larger air gap, skewing of the stack, and special winding configurations.

If cost is also considered as a major trade concern, then the system trade analysis can become fairly complex. The most critical aspect of the trade analysis is making sure that the torque disturbance ripple and cogging requirements are not any more restrictive than necessary. Otherwise, the usual engineering conservatism applied to disturbance requirements can drive the design costs and system complexity well beyond what is actually required. A careful system analysis early in the design phase using a "team" approach is recommended; this should include a motor design specialist to help optimize the system design and specified requirements.

Table 1.0 – Motor Design Trade-offs for
Low Torque Disturbance Space Mechanisms

Motor Design Approach Options	**Commutation and System Description**	**Torque Disturbance Ratings**	**Benefits**	**Negatives**
2-Phase BLDC Motor with integral slots per pole	Resolver Commutation & Sinusoidal Excitation	BEST	Lowest ripple & low cogging.	Difficult to manufacture and some loss in Km.
3-Phase BLDC Motor with fractional slots per phase per pole	Resolver Commutation & Sinusoidal Excitation	VERY GOOD	Low ripple and cogging. No skew.	Easier to fabricate than 2-phase. Some loss in Km.
3-Phase BLDC Motor Without Iron Teeth	Resolver Commutation & Sinusoidal Excitation	VERY GOOD	Low ripple & Zero cogging. Sinusoidal driver closely matches current with back EMF.	Significant loss in Km due to large air gap.
3-Phase BLDC Motor with skewed stack or non-integral slots per pole	Hall Effect Commutation and Six-step Excitation	GOOD	Moderate ripple depends on motor design. Low cogging. Simple Hall Effect Six-step system.	Only the most careful designs will have lower torque disturbance than conventional Six-step motors.
3-Phase BLDC Motor Without Iron Teeth	Hall Effect Commutation and Six-step Excitation	FAIR	Moderate to high torque ripple. Zero cogging with Simple Hall Effect Six-step system.	Significant loss in Km. Trapezoidal driver is not closely matched with back EMF giving increased torque ripple.

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