

Standard

Moving Mechanical Assemblies for Space and Launch Vehicles

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Standard

Moving Mechanical Assemblies for Space and Launch Vehicles

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

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Abstract

This standard specifies general requirements for the design, manufacture, quality control, testing, and storage of moving mechanical assemblies (MMAs) to be used on space and launch vehicles. This standard is applicable to the mechanical or electromechanical devices that control the movement of a mechanical part of a space or launch vehicle relative to another part. The requirements apply to the overall MMA as well as to the mechanical components and instrumentation that are an integral part of these mechanical assemblies.

The most significant updates in this revision, relative to the previous (2005) version, include a reformatted and rewritten testing section, a new approach to calculating force/torque margin, and the elimination of the “shall, where practical” weighting level of requirements.

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Foreword

This standard is originally based on Military Specification MIL-A-83577B, Moving Mechanical Assemblies (MMA) for Space and Launch Vehicles, which was superseded by AIAA S-114 in 2005.

This standard is the result of contributions received from many individuals, most notably those on the AIAA MMA Committee on Standards (CoS).

At the time of approval, the members of the AIAA MMA CoS were:

Mark Balzer	Jet Propulsion Laboratory
Ed Boesiger	Lockheed Martin Corporation
Brian Gore (Co-chair)	The Aerospace Corporation
Leon Gurevich (Co-chair)	The Aerospace Corporation
Ray McVey	Raytheon Company (retired)
Michael Pollard	Lockheed Martin Corporation
Brandan Robertson	NASA Johnson Space Center
Adam Sexton	Ball Aerospace & Technologies Corporation
Timothy Woodard	The Aerospace Corporation

Introduction

This standard is intended to incorporate the requirements that are common to most Moving Mechanical Assemblies (MMAs) for space and launch vehicles. The requirements stated are a composite of those that have been found to be cost-effective for high reliability space and launch vehicle applications.

Not all provisions stated herein are of equal importance or weight. They have been divided into two categories of importance:

“Shall” designates the mandatory requirements. Unless specifically tailored out or modified by the contract, they constitute the firm contractual compliance requirements. All instances of “**SHALL**” requirements in this standard have been highlighted for ease of recognition.

“Preferred,” “should,” or “may” designate guidelines. Unless required by other contract provisions, deviations from these preferred guidelines do not require approval and do not require documented technical substantiation. Although these guidelines are not requirements, they reflect the preferred principles and lessons learned based on a wealth of industry-wide experience and proven design, analysis, and test approaches.

1 Scope

This standard specifies general requirements for the design, manufacture, quality control, testing, and storage of moving mechanical assemblies (MMAs) to be used on space and launch vehicles. This standard is applicable to the mechanical or electromechanical devices that control the movement of a mechanical part of a space or launch vehicle relative to another part. The requirements apply to the overall MMA as well as to the mechanical components and instrumentation that are an integral part of these mechanical assemblies.

When this standard is used to specify general requirements for MMAs to be used on launch vehicles, injection stages, reentry vehicles, or other vehicles, the term “space vehicle” is to be interpreted as the applicable vehicle.

2 Tailoring

Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

Where possible, the requirements in the standard are stated in terms that are self-tailoring to each application. However, additional tailoring of the requirements should be considered throughout the acquisition process within the constraints of the major program elements. These elements typically include performance, testing, reliability, schedules, production costs, operating costs, maintenance costs, and other high-cost drivers in the projected life cycle. Contractors are encouraged to identify to the procurement authority, for program office review and reconsideration, any requirements imposed by this standard that are believed excessive. However, contractors are reminded that deviations from contractually imposed requirements can be granted only by the procurement authority.

The use of the weighting factors (see Introduction) in the standard is intended to assist in the tailoring of requirements to specific applications and to assist contractors in the design process. Because the implications of the weighting factors vary with the type of contract and with other contract provisions, it is important to provide clear contractual language, particularly regarding design reviews and the resolution of any subsequent actions.

3 Applicable Documents

The following documents and publications form a part of this standard to the extent specified herein. Unless otherwise specified, the most recent version is applicable.

In the event of a conflict between the text of this standard and the references cited, the text of this standard **SHALL** take precedence. Nothing in this standard, however, **SHALL** supersede applicable laws and regulations unless a specific exemption has been obtained.

ABMA STD 3290-1	Rolling Bearings - Balls - Part 1: Steel Balls
Aerospace TR-RS-2014-00016	Test Requirements for Launch, Upper-Stage, and Space Vehicles
AGMA Handbook	American Gear Manufacturers Association Handbook
AIAA S-110-2005	Space Systems – Structures, Structural Components, and Structural Assemblies
AIAA S-113A-2016	Criteria for Explosive Systems and Devices on Space and Launch Vehicles
ASTM F2094	Standard Specification for Silicon Nitride Bearing Balls
ASTM F2215	Standard Specification for Balls, Bearings, Ferrous and Nonferrous for Use in Bearings, Valves, and Bearing Applications
ATR-2009(9369)-1	Critical Clearances in Space Vehicles (The Aerospace Corporation)
MIL-STD-1686	Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices)
MIL-PRF-46010	Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting
NASA-STD-5020A	Requirements for Threaded Fastening Systems in Spaceflight Hardware
SMC-S-016	Test Requirements for Launch, Upper-Stage, and Space Vehicles

4 Vocabulary

For the purposes of this document, the following terms and definitions apply.

Addendum

The radial height of an involute gear tooth above the pitch line.

NOTE: A long addendum modification is often specified on a pinion to balance the tooth bending stress between the pinion teeth and gear teeth, and to lower and balance the specific sliding ratios.

Back Electromotive Force (EMF)

The voltage generated in an inductive coil or motor winding when the inductive coil or motor winding is exposed to a time-varying magnetic field.

Boundary Regime

Condition that occurs when the thickness of a fluid film separating two surfaces is less than the composite surface roughness. This may occur due to heavy loads, low viscosity, liquid lubricant scarcity, or low speeds.

NOTE: In the boundary regime, asperity contacts are common, and the properties of their interaction (i.e., dry friction coefficient and plastic flow stress) dominate the resistance to motion. Operation in this regime may result in elevated friction force, heat generation, and wear rate.

Cold Welding, Seizing, and Galling

Adherence of same or similar material parts, such as fasteners or cup-cone fittings, under high interface contact pressures, extended periods in vacuum conditions, and/or where small motions are induced at the preloaded interface.

Component

An item containing two or more parts, which is capable of disassembly or part replacement. Examples: rolling element bearing, gearbox, motor, damper.

Constant Velocity Torque/Force Margin

Constant velocity torque margin is a measure of the excess torque available to maintain motion.

Contact Ellipse

The area formed by a bearing ball loaded against the raceway groove in a bearing ring in a ball bearing assembly.

Contact Ratio

The number which indicates the average number of pairs of gear teeth in contact.

NOTE: It can be calculated by the arc of action (circumferential length along the pitch diameter from one tooth to the corresponding point on the next tooth) divided by the circular pitch.

Critical Component or Assembly

An item not backed up by a redundant unit or function, or whose failure could cause complete loss of the space vehicle or the loss of a primary portion of the mission.

Dedoidal Condition

A condition in harmonic drives in which the flexspline is not symmetrically engaged with the circular spline as can occur during installation, mishandling, or torque overload.

Deployable

A device that is moved by a moving mechanical assembly from a stowed position to an extended position.

NOTE: Solar arrays, antennas, experiment booms, or sun shields are classified as deployables where they meet the above description. The term “deployable” should be interpreted as inclusive of all devices that are deployed, retracted, or stowed.

Dynamic Torque/Force Margin

Dynamic torque margin is a measure of the excess torque available to accelerate a body by a given amount.

Elastohydrodynamic Lubrication Regime

Situation in which gear teeth, or a rolling element and race, generate a self-pressurizing coherent fluid film between them of sufficient thickness, based on load and speed, while they are elastically deformed under load; asperity contact may or may not exist in the EHD regime.

Failure

An event or condition that causes the device or system to perform outside of its specification limits.

NOTE: The failure modes include those associated with performance, premature operation, failure to operate at a prescribed time, failure to cease operation at a prescribed time, and others that are unique to the device or system.

Flash Temperature

In gearing, the increase in temperature at the contact area between mating teeth due to heat generated from sliding friction.

Galling

A form of surface damage arising between sliding solids, distinguished by macroscopic, usually localized, roughening and creation of protrusions above the original surface; it often includes plastic flow, material transfer, or both.

Holding Torque/Force Margin

A measure of the excess torque available to maintain position in the presence of external disturbances.

Hunting Tooth

A condition in which the number of teeth on the driven and driving gears is selected so that the same two teeth do not mesh with each revolution of the larger of the two gears.

NOTE: The number of teeth on each gear should be selected, within the limits of the gear ratio requirement, to maximize the number of revolutions before meshing of the same two teeth.

Limit Load

The highest expected load or combination of loads that a structure or a component in a structural assembly may experience during its service life in association with the applicable operating environments.

Locking Feature

A device, chemical substance, or other physical characteristic added by design to one or more elements of a threaded fastening system to resist vibration-induced loosening or to provide retention against complete disengagement of the fastening elements.

Movable System

A device or system that requires a moving mechanical assembly to orient, rotate, track, scan, or otherwise control position or motion.

NOTE: Movable systems include, but are not limited to, antennas, telescopes, sensors, control-moment gyroscopes (CMGs), momentum wheels, and reaction wheels. A deployable is a type of movable system.

Moving Mechanical Assembly (MMA)

A device that controls the movement of a deployable or other movable system of a space or launch vehicle.

NOTE: Moving mechanical assemblies include, but are not limited to, deployment mechanisms, sensor mechanisms, pointing mechanisms, drive mechanisms, de-spin mechanisms, separation mechanisms, momentum and reaction wheels, control-moment gyros, gimbals, switches, valves, and other mechanisms required to perform specific functions.

Profile Shift

In gearing, the amount by which the reference plane of the cutting tool is displaced from the reference diameter (pitch circle) of the gear.

NOTE: Positive profile shift is frequently specified on low tooth number pinions to reduce or eliminate undercutting and its associated bending stress increase. Profile shift is typically specified by the non-dimensional "profile shift coefficient" (sometimes called a "rack shift coefficient" or an "addendum modification coefficient"), defined as the profile shift times the diametral pitch of the gear, or as the profile shift divided by the normal module of the gear.

Proof Load

The load applied during acceptance proof testing. The proof load is greater than the limit load by a factor (proof factor) depending on the item being tested (see Ref. 3).

Pull-in Torque

The maximum constant torque for a given speed, inertial load, and controller/driver under which a stepper motor will accelerate from rest to operating speed, stop, or reverse direction in synchronism with input pulses (i.e., without loss of steps).

NOTE 1: Pull-in torque is determined using 100% pulse duty cycle unless defined otherwise.

NOTE 2: Pull-in torque includes detent torque and motor bearing friction.

Pull-in Torque Margin

Pull-in torque margin is a measure of the excess torque available to accelerate a stepper motor from rest to operating speed, stop a stepper motor, or reverse direction of a stepper motor in synchronism with input pulses (i.e. without loss of steps) for a given operating speed, inertial load, and controller.

Pyrotechnically Actuated Device

A mechanism that employs the energy produced by an explosive charge to perform or initiate a mechanical action.

Service Life

The period of time encompassing the acceptance testing, handling, storage, transportation, launch operations, orbital operations, refurbishment, retesting, reentry or recovery from orbit, and reuse that may be required or specified for the item.

Single-point Failure

The failure of an individual element that causes the failure of the entire system.

NOTE: A single-point failure mode within a redundant device of a system is therefore typically not a single-point failure mode of that system. If it is, the devices are not completely redundant.

Static Load

The static load is the load applied during a qualification static load test. The static load is greater than the limit load by a factor of safety (see Ref. 3).

Static Torque/Force Margin

A measure of the excess torque available to overcome resistance to impending motion.

Step Integrity

The ability of a stepper motor system to achieve the number of steps commanded without loss or gain of steps.

Stopping Load

The deceleration load or end-of-travel load imparted to the MMA and/or the surrounding structure.

NOTE: The maximum stopping load can occur at end of travel or at intermediate points of travel, as in the case of damper dead band.

Subsystem

An assembly of functionally related units, including any associated software. It consists of two or more units and may include interconnection items such as cables or tubing, and the supporting structure to which they are mounted. Example: Two axis gimbal mounted to its support structure, and including electrical harness, telemetry instrumentation, thermal blankets or insulation, and payload elements.

Truncation

Situation in which applied loads cause a portion of a bearing ball's contact ellipse to extend beyond the edge of the raceway groove.

Ultimate Load

The limit load multiplied by the ultimate factor of safety; factors can be found in AIAA S-110-2005.

Unit

A functional item that is viewed as a complete and separate entity for purposes of manufacturing, maintenance, record keeping and environmental/performance testing. Examples: hinge, actuator, valve, slip ring, reaction wheel.

Yield Load

The limit load multiplied by the yield factor of safety; factors can be found in AIAA S-110-2005.

5 General Design Requirements

5.1 Performance Requirements

5.1.1 General Performance Requirements

Deployables and other movable systems should be designed so that they are self-supporting when placed in any orientation relative to gravity, while in either the stowed or deployed configuration. They **SHALL** be designed with sufficient motive force to permit full operation during ground testing without depending on the assistance of gravity to demonstrate deployment. Off-loading devices to simulate a zero “g” condition are allowed so that the movable system is adequately supported. Off-loading devices should have minimal effect on deployment; these effects **SHALL** be included in operational analyses. Where a device rotates after deployment, as in sun-tracking solar arrays, the design should be such that the center of gravity of the device is coincident with the axis of rotation to preclude the need for counterbalancing during functional testing.

For all deployables, the deployment motion should be controlled for the full range of travel. For all deployables, rebound of the deployable after contacting the stops should be minimized.

Kick-off springs or similar devices **SHALL** be used to ensure complete disengagement of the deployable from any retention mechanism.

Where acceleration loads are applied to a deployed assembly, such as those generated by space vehicle spin or propulsion forces, the design should preferably be such that the accelerations tend to drive the deployable into its deployed latched position.

Positive retention devices **SHALL** be provided for deployables in the stowed position. Positive retention devices should be provided for deployables in the deployed position.

Where two or more deployables are used on a space vehicle, the deployment/operation of one should not be dependent on the successful deployment or operation of the other.

5.1.2 Torque/Force Margins

Torque (or force) margin is a measure of the excess capability of an MMA to impart, maintain, or prevent motion, or provide required acceleration.

In this section, references to “torque margin” also apply to linear motion, with “force” replacing “torque.” MMAs should be designed with the highest practical torque margin, although it should be recognized that in the design of some systems, excessive torque margins may be detrimental. Additionally, torque margin is not applied to MMAs that must provide a specific torque value within a narrow tolerance range in order to perform their basic function, such as a spring holding a relief valve closed, or an ejection mechanism requiring a specific (not minimum) separation velocity.

All torque margins **SHALL** be greater than zero at every point within the MMA’s full range of travel, and under worst-case conditions, throughout its life, including life testing.

Worst-case conditions are defined as those that result in a combination of minimum driving torque and maximum resisting torque over the range of qualification environmental limits (e.g., temperature, pressure, acceleration, vibration, radiation, humidity), operating limits (e.g., supply voltage, motor/controller parameters), and design parameters (e.g., material properties, manufacturing tolerances, spring force variability).

Only those worst-case combinations that can occur simultaneously **SHALL** be used in torque margin calculations. For example, if the minimum driving torque occurs at hot conditions, and the maximum resisting torque occurs at cold conditions, then the two should not be combined to calculate a torque margin. As another example, if the minimum driving torque and maximum resisting torque do not occur at the same point in an MMA’s range of motion, then the two should not be combined to calculate a torque margin.

For MMAs that use torque multipliers/reducers (such as gearboxes or harmonic drives), torque margin requirements **SHALL** be met at both the input and output of such components.

5.1.2.1 Torque/Force Margin Calculation

Calculation of static torque margin, dynamic torque margin, constant velocity torque margin, and holding torque margin **SHALL** be performed on all MMAs using Equation 1 and Table 1.

$$\text{Torque Margin} = \frac{T_{\text{avail}}}{\sum K_{\text{fix}} T_{\text{fix}} + \sum K_{\text{var}} T_{\text{var}} + \sum K_{\text{acc}} T_{\text{acc}}} - 1 \quad (\text{Equation 1})$$

T_{avail} is the minimum available torque generated by the driving or holding component (e.g., spring, motor). T_{avail} **SHALL** be determined using worst-case conditions including spring material properties and tolerances, or in motors, supply voltage and motor/controller parameters (including environmental conditions). Internal parameters of electric motors such as cogging and magnetic detent are considered to be included in the net output driving torque of the motor.

T_{fix} terms are the individual maximum “fixed” resisting torques that are not strongly influenced by effects of friction, temperature, cycles, etc. (e.g., motor detent torque, vehicle maneuver-induced torque, return spring torque, unbalanced pressure load limited by relief mechanisms).

T_{var} terms are the individual maximum “variable” resisting torques whose values may change with environmental conditions and cycles (e.g., friction torque, wire harness torque due to flexing or long term set).

T_{acc} is the torque required to achieve the specified acceleration of the driven component.

T_{fix} , T_{var} , and T_{acc} **SHALL** be determined using the worst-case conditions including friction, alignment effects, latching forces, return springs, wire harness torque (e.g., flexing, long term set), damper drag, acceleration due to vehicle motion or maneuvers, and variations in lubricity (including environmental conditions). The calculation of resisting torque in assemblies with viscous dampers **SHALL** include the seal friction due to mechanical compression of elastomers, fluid pressure on the elastomers, and possible changes due to storage time.

K_{fix} , K_{var} , and K_{acc} are the fixed, variable, and acceleration torque/force margin factors applied to each individual resisting torque/force term in Equation 1 prior to summation. Table 1 specifies those minimum torque/force margin factors to be used in Equation 1, based on the source of the torque/force data.

Table 1 – Minimum Torque/Force Margin Factors

Source of Torque/Force Data	K_{fix}	K_{var}	K_{acc}
Theory or analysis	1.50	3.00	1.25
Test of engineering model, development, qualification, or lot acceptance hardware at respective environmental conditions; or flight hardware at ambient conditions	1.35	2.50	1.15
Test of flight hardware at acceptance environmental conditions	1.25	2.00	1.10
Value for one-spring-failed case	1.00	1.00	1.00

For those systems where the observed values of the driving and resisting torques are small and difficult to test, are poorly characterized, or are highly variable, torque/force margin factors greater than those specified in Table 1 should be used.

In spring-driven MMAs where multiple springs are used additively to provide redundancy, the MMA **SHALL** have positive torque margin for a one-spring-failed case using the torque/force margin factors in Table 1. Spring-driven MMAs should be designed to minimize resisting torque from broken springs.

5.1.2.2 Types of Torque/Force Margin

Static Torque/Force Margin

Static torque margin is a measure of the excess torque available to overcome resistance to impending motion. The static torque margin **SHALL** be calculated using Equation 1 with static friction and static resisting torque values. T_{acc} is not used in the static torque margin calculation in Equation 1.

Constant Velocity Torque/Force Margin

Constant velocity torque margin is a measure of the excess torque available to maintain motion. For MMAs that must operate at a constant velocity, the constant velocity torque margin **SHALL** be calculated using Equation 1 with kinetic friction and kinetic resisting torque values. In addition to typical resistances such as Coulomb friction and wire harness torque, damper and back-EMF torques should also be included in the calculation, if applicable. T_{acc} is not used in the constant velocity torque margin calculation in Equation 1.

Holding Torque/Force Margin

Holding torque margin is a measure of the excess torque available to maintain position in the presence of external disturbances. For MMAs that require a holding torque, the holding torque margin **SHALL** be calculated using Equation 1 with the maximum disturbance torque(s) as the T_{fix} and/or T_{var} term(s), depending on the source of the disturbance. T_{avail} is the minimum powered or unpowered holding torque available to hold position from sources such as brakes, springs, latches, or motor detents. Passive friction sources (e.g., joint friction, harness bending, blanket rubbing) contributing to holding torque **SHALL** be excluded from T_{avail} . T_{acc} is not used in the holding torque margin calculation in Equation 1. In applications using stepper motors, and vibratory disturbances are present, detent stiffness and motor damping **SHALL** be used in determining margin.

Dynamic Torque/Force Margin

Dynamic torque margin is a measure of the excess torque available to accelerate a body by a given amount. For MMAs that require a specific acceleration, the dynamic torque margin **SHALL** be calculated using Equation 1, with kinetic friction and kinetic resisting torque values as the T_{fix} and T_{var} terms, and torque required for acceleration as the T_{acc} term. Separation systems with a requirement for minimum separation velocity are also subject to the dynamic force margin calculation.

Values of mass and moment of inertia used in dynamic force/torque margin calculations **SHALL** include allowances for system growth over the duration of a program. These allowances are typically specified in a program mass growth allocation document.

5.1.2.3 Stepper Motor Margin

The stepper motor margin **SHALL** be calculated using either a step stability analysis or a pull-in torque margin analysis. The step stability analysis is preferred, but the pull-in torque method is also acceptable when all of the following conditions are met:

- the load at the motor due to friction is much greater than the driven inertial load
- structural modes of the mounting base and driven inertia are greater than stepping rate
- the driven inertia is not driven into a hard stop or spring stop
- the motor winding current is applied to the motor during the entire step
- the pull-in torque test environment is applicable to the operating environment

Step stability analysis **SHALL** be used to determine stepper motor margin when any of the conditions above do not

apply.

The worst-case combination of torques under the worst-case environmental conditions **SHALL** be used to evaluate the stepper motor margin.

When using the pull-in torque margin method, the margin can be calculated using Equation 1, with the pull-in torque for a given drive rate as the T_{avail} term, and the total torque seen by the stepper motor as the T_{var} term, as shown in Equation 2 below. T_{fix} and T_{acc} are not used when calculating pull-in torque margin.

$$\text{Pull-in Torque Margin} = \frac{\text{Pull-in Torque at Drive Rate}}{K_{var} * \text{Total Friction Load Seen by Motor}} - 1 \quad (\text{Equation 2})$$

When using the step stability method to calculate the torque margin, Equation 2 can be rewritten as:

$$\text{Pull-in Torque at Drive Rate} = [1 + \text{Pull-in Torque Margin}] * [\text{Total Friction Load Seen by Motor}] \quad (\text{Equation 3})$$

Step stability is achieved when the left side of Equation 3 is greater than the right side. In the step stability analysis, the value of the $[1 + \text{Pull-in Torque Margin}]$ term is increased until the motor goes unstable. The value from the last stable case is then used to calculate the stepper motor margin. The stability margin in all cases **SHALL** be positive, that is, step integrity **SHALL** be maintained for all combinations of parameters.

Stepper motor margin is established by varying the design parameters individually and in combination. Combinations of parameters can be analyzed in a worst-on-worst fashion or by using a Monte Carlo simulation. The stability analysis should consider the following parameters in the stepper motor system:

- motor inductance manufacturing variations
- motor resistance — consider manufacturing and thermal variations
- input voltage and current characteristics — consider variations in pulse shape and timing and operational states such as tracking and slewing
- step angle size — consider variations from step to step
- voltage constant — consider range due to manufacturing tolerances and temperature effects
- powered holding torque — consider range due to manufacturing tolerances, temperature effects, and current tolerance
- motor back-EMF constant
- motor detent properties
- rotor damping, viscous damping from motor bearings, lubricant, and magnetic structure — consider manufacturing tolerances, service life cycles, and thermal effects
- rotor friction, from motor bearings — consider manufacturing tolerances, life, and thermal effects
- rotor inertia — consider manufacturing variation
- motor rotor to gear train stiffness
- motor rotor to gear train deadband — consider manufacturing and thermal variations
- drag torque from slip-rings, bearings, and gears/harmonic drives

- gear train inertia, stiffness, and deadband – consider manufacturing variations
- gear train damping — consider effects of thermal and aging
- gear train torque variation such as transmission error or harmonic drive two-cycle torque variation
- load inertia and variations due to manufacturing
- modal properties of the load
- stop stiffness and variations in stiffness due to manufacturing
- modal properties of the base including base motion disturbances
- test conditions, test equipment effects, and one “g” effects

5.1.3 Error Budget for Precision Control Assemblies

For MMAs used in pointing applications where precision control is necessary, the error budget **SHALL** include performance errors due to misalignments, deflections, dynamic loads, thermal distortions, control system transients, steady state errors, friction, friction noise (friction or torque variations), friction hysteresis, structural and mechanical hysteresis, backlash, drive motor ripple, quantization errors in command and feedback sensors, and any other defined error sources.

5.1.4 Dynamic Performance

Dynamic analyses **SHALL** include resonant frequency effects, damping characteristics, and dynamic loading effects such as cyclic/harmonic disturbances from gear errors, bearing noise, motor ripple, or end-of-travel loads. Dynamic analyses **SHALL** include any effects from resonant amplification effects of the surrounding structure, changes in mass properties and momentum balance, and transient torques during operation of the MMA or operation of the space vehicle.

5.1.5 Off-nominal Operation

The sensitivity of the design and operational performance to changes in various parameters should be considered and minimized. The design sensitivity should be substantiated by analysis or tests conducted to determine the effects of various off-nominal parameters which are beyond design requirements. These off-nominal parameters should include, but not be limited to, such items as the following:

- higher dynamic response of surrounding structure
- higher and lower speed of motors
- higher and lower velocities of deployables
- varying duty cycles
- misalignments
- friction due to contamination
- overload and heating of motors due to stalling
- inadvertent spin-up of the de-spun portion of dual-spin space vehicles
- inadvertent spin-up of three-axis-controlled space vehicles
- higher and lower spin speeds of spinning space vehicles

- thruster firings
- higher and lower nutation frequencies associated with spinning space vehicles
- unsymmetrical deployment of solar arrays
- transient over-voltage
- high and low bus voltage
- power-down modes
- off-nominal environmental conditions, including such changes in environmental conditions as those caused by a delay in deployment of a device until a subsequent ground station contact

5.2 Environmental Design Requirements

MMA's **SHALL** be designed to meet all performance requirements when exposed to (proto)qualification environmental levels in accordance with the definitions in Aerospace TR-RS-2014-00016.

5.2.1 Launch Environment

Analysis or other verification methods **SHALL** verify that MMA's function within performance specifications after exposure in the launch configuration to the maximum launch or other non-orbital service environments. These environments may include temperature, vibration, acoustic noise, shock, acceleration, atmospheric pressure including high pressure or vacuum, humidity, low-pressure-induced corona, and electrical storms with associated radiation.

5.2.2 On-orbit Environment

Analysis or other verification methods **SHALL** verify that MMA's function within performance specifications following or, if required, during exposure to the specified environments. These environments may include thermal, high pressure or vacuum, atomic oxygen, micrometeoroids, radiation, shock, random vibration, and acceleration.

5.2.3 Fabrication, Storage, Transportation, and Handling Environments

Environmental conditions (including cleanliness, temperature, acceleration, and humidity) throughout storage, fabrication, handling, and transportation, **SHALL** not exceed maximum specified limits. Sputter-deposited, burnished, or air-impinged molybdenum disulfide or tungsten disulfide solid film lubricants should be protected by a dry nitrogen purge or other suitable means of excluding humidity during the storage, testing, and prelaunch environments. Oxidation resulting from humid air absorption is not a reversible process, and will continue to degrade the lubricant with increasing time while the MMA is operating or at rest. The onset of corrosion in low chromium steels (e.g., 52100) is virtually instantaneous in air during relative motion, even when covered with oil films. As such, these steels **SHALL** be continually maintained in a dry nitrogen, vacuum, or other inert environment during all testing.

MMA's **SHALL** be capable of meeting the operational requirements without refurbishment, other than relubrication, after a non-operational storage period dictated by program requirements. If the non-operational storage period is exceeded, all components should be reviewed for life issues. Cycling the MMA should be considered to counteract the effects of oil separation during storage. The orientation or storage environment or both should be chosen to minimize oil flow within the assembly. Storage should be in a "no-load" condition with springs in a relaxed state. Pressure vessels should be unpressurized except where pressure stabilization is required.

For hardware that can be adversely affected by temperature, humidity, and/or shock, exposure levels **SHALL** be monitored subsequent to manufacture, and the measured levels **SHALL** be evaluated against the acceptance test limits.

5.3 Physical Requirements

5.3.1 Identification and Marking

MMA and interchangeable components **SHALL** be identified in such a manner as to not cause damage or interfere with operation.

Items that by intent or by material disposition are not suitable for use in flight, and that could be accidentally substituted for flight or flight spare hardware, **SHALL** be conspicuously marked to prevent such substitution.

5.3.2 Interface Requirements

5.3.2.1 Clearance

The clearance requirements within the MMA and between the MMA and any other structure, component, and field of view **SHALL** be established and maintained. The manufacturing, assembly, and alignment tolerances that affect moving clearances, as well as environmental conditions such as temperature, temperature gradients, vibration, distortion due to relaxation of the “g” field, effects of centrifugal forces, and acceleration during the critical periods of launch and on-orbit operations, **SHALL** be included in establishing clearance requirements. The established clearances **SHALL** be maintained during transportation and all operational modes of the space vehicle.

Establishment of MMA clearance requirements **SHALL** include effects of thermal blankets (including billowing), tape, and electrical harnesses that may reduce or eliminate clearances, impeding motion of the MMA.

5.3.2.2 Alignments

Provisions **SHALL** be included to ensure alignment of MMAs with respect to the next higher assembly and other subsystem elements if alignments cannot be controlled by drawing tolerances. A shimming-type alignment technique may be used where additional surface area is necessary to provide a bearing surface or where electrical bonding is required. Where an adjustable-type alignment technique is used, locking provisions as specified in the Fasteners section of this document **SHALL** be provided. Installation of alignment pins is permissible if the pins are positively retained and permit the MMA to be easily removed.

5.3.2.3 Mechanical

A common interface drill template may be used to ensure correct mechanical mating, particularly for interfaces external to the MMA.

Field joints should be provided to permit disassembly of all MMAs, deployables, and other movable systems from the next higher assembly to facilitate testing or replacement of parts.

In selecting the design for the structural interface of the MMA with the space vehicle, preference should be given to simple approaches that minimize the complexity of the interface. The MMA should be easily installed and readily accessible for inspection or removal. Sufficient tool clearances **SHALL** be provided. The use of special tools should be minimized.

5.3.3 Operability

5.3.3.1 Human Engineering

The design of all MMAs **SHALL** be such that they may be tested or inspected to ensure that they are assembled and installed correctly. Provisions such as tabs and shoulders should be used to prevent assembly in any incorrect manner that may impair the intended functions of the MMA.

5.3.3.2 Safety

MMAs, particularly those associated with deployables, **SHALL** be protected from damage that may occur at any stage of the fabrication, assembly, testing, or transportation.