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Space Systems — Mechanism design and verification

Systèmes spacieux — Conception et vérification des mécanismes

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Mechanisms are important elements of spacecraft and its payloads. A mechanism failure can cause the loss of human lives for manned space systems or jeopardize the intended mission for unmanned space systems.

Currently, there is no international standard that covers all the aspects that can be used for space flight moving mechanisms such as rotating machineries, solar array drive mechanism, paddle hinge mechanism, latch mechanism.

The purpose of this document is to establish general requirements for mechanisms. It provides the uniform requirements necessary to minimize the duplication of effort for resolving technical barrier, considering the differences between approaches taken by the participating nations and their commercial space communities in developing mechanisms. In addition, the use of agreed-upon standards will facilitate cooperation and communication among space programmes.

This document, when implemented for a particular space system, ensures high confidence in achieving safe and dependable operation in all phases of its planned mission.

Space Systems — Mechanism design and verification

1 Scope

This document establishes requirements for the design, material selection and characterization, fabrication, testing and inspection of all space mechanisms on spacecraft and payloads to meet the mission performance requirements. This document does not cover the requirements for mechanisms on expendable and reusable launch vehicles. Applicability of the requirements contained in this document to launch vehicle mechanisms is a decision left to the individual launch vehicle project.

This document applies specifically to all moving mechanisms used in spacecraft during all phases of the mission, with the exception of engines and thermal protection systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10786, *Space systems — Structural components and assemblies*

ISO 14302, *Space systems — Electromagnetic compatibility requirements*

ISO 15864, *Space systems — General test methods for spacecraft, subsystems and units*

ISO 21886, *Space systems — Configuration management*

ISO 23135, *Space systems — Verification program and management process*

ISO 23460, *Space projects — Programme management — Dependability assurance requirements*

ISO 24113, *Space systems — Space debris mitigation requirements*

ISO 27025, *Space systems — Programme management — Quality assurance requirements*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
mechanism
assembly of parts that are linked together to enable a relative motion

3.2
outgassing
evolution of gaseous species from a material, usually in a vacuum

Note 1 to entry: Outgassing also occurs in higher-pressure environments.

[SOURCE: ISO 15388:2012, 3.1.34]

3.3
interface
mechanical, thermal, electrical, or operational common boundary between two elements of a system

[SOURCE: ISO 10795:2019, 3.132]

3.4
acceptance test
required formal test conducted on flight hardware to ascertain that the materials, manufacturing processes, and workmanship meet specifications and that the hardware is acceptable for intended usage

[SOURCE: ISO 10786:2011, 3.2]

3.5
contamination
introduction of any undesirable molecular or particulate matter (including microbiological matter) into an item or into the environment of interest

[SOURCE: ISO 10795:2019, 3.62]

3.6
lubrication
use of specific material surface properties or an applied material between two contacting or moving surfaces in order to reduce friction, wear or adhesion

3.7
redundancy
⟨design property of a system⟩ existence of more than one means for performing a function

Note 1 to entry: The additional means of performing the function may be intentionally different (diverse) to reduce the potential for common mode failures.

[SOURCE: ISO 10795:2019, 3.196]

3.8
debris
fragment such as abrasion powders produced by the operation of *mechanism* (3.1) parts

Note 1 to entry: See also *space debris* (3.18).

3.9
tribology
discipline that deals with the design, friction, wear and *lubrication* (3.6) of interacting surfaces in relative motion to each other

3.10
qualification test
required formal contractual test used to demonstrate that the design, manufacturing, and assembly have resulted in hardware designs conforming to specification requirements

[SOURCE: ISO 10795:2019, 3.187]

3.11
maintainability
⟨of an item⟩ ability to be retained in, or restored to a state in which it can perform as required, under given conditions of use and maintenance

Note 1 to entry: Given conditions of use may include storage.

Note 2 to entry: Given conditions of maintenance include the procedures and resources for use.

Note 3 to entry: Maintainability may be quantified using such measures as mean time to restoration, or the probability of restoration within a specified period of time.

[SOURCE: ISO 10795:2019, 3.144]

3.12
misalignment
geometric position error between machine elements and parts

EXAMPLE Translational displacement, inclination, torsion.

3.13
mission
set of tasks, duties or functions to be accomplished by an element

[SOURCE: ISO 10795:2019, 3.154]

3.14
latching
locking
intentional constraining of one or more previously unconstrained degrees of freedom which cannot be released without specific action

3.15
model
physical or abstract representation of relevant aspects of an **item** or **process** that is put forward as a basis for calculations, predictions, or further assessment

Note 1 to entry: The term "model" can also be used to identify particular instances of the **product**, e.g. flight model.

[SOURCE: ISO 10795:2019, 3.155]

3.16
modelling
act of creating a *model* (3.15), i.e. act of creating a representation of a system

3.17
simulation
imitation of the behavioural characteristics of a system, entity, phenomenon, or process

Note 1 to entry: The term "simulation" can be also used for the production of a computer (or physical) *model* (3.15) of something, especially the purpose of study.

3.18
space debris
objects of human origin in Earth orbit or re-entering the atmosphere, including fragments and elements thereof, that no longer serve a useful purpose

[SOURCE: ISO 24113:2019, 3.23, modified — The deprecated term and note 1 to entry have been removed.]

3.19
dependability
<of an item> ability to perform as and when required

Note 1 to entry: Its main components are reliability, availability and *maintainability* (3.11).

Note 2 to entry: The extent to which the fulfilment of a required function can be justifiably trusted.

Note 3 to entry: Dependability shall be considered in conjunction with safety.

Note 4 to entry: Dependability is used as a collective term for the time-related quality characteristics of an item.

[SOURCE: IEC 60050-192:2015, 192-01-22, modified — The original note 1 to entry has been replaced by Notes 1 to 3 to entry.]

3.20
electromagnetic compatibility
EMC
ability of a space equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[SOURCE: ISO 14302:2002, 3.1.4]

4 Fundamental requirements

4.1 System performance

The mechanism functional performance shall conform to the system performance requirements allocated to the mechanism.

4.2 Mission

Design of the mechanism shall meet the requirements applied throughout the entire period of the mission specified in individual programs. Design of the mechanism shall meet all requirements and encountered environmental conditions in each phase of the mission.

4.3 Function

a) The kinematic requirements applicable to each position change shall be specified.

NOTE 1 For example, position over time, velocity and acceleration.

b) Mechanical interface, position accuracy or velocity tolerances shall be specified and verified that they meet the functional needs.

NOTE 2 Mechanical interfaces include assembly and test rigging and other installation and integration conditions.

c) The envelope of movement for each moving part shall be defined.

d) It shall be ensured that there is no mechanical interference between the movement of each part with any other part of the mechanism, the spacecraft, the payload or the launch vehicle.

5 Design requirements

5.1 Interfaces

a) Structural interfaces

Mechanisms shall conform to the structural interface conditions and requirements defined in the specification.

b) Thermal interfaces

Mechanisms shall conform to the thermal interface conditions and requirements defined in the specification.

c) Thermo-mechanical interfaces

Mechanisms shall be designed in consideration of thermal stress induced between the mechanism and its installation points.

d) Electrical interfaces

Mechanisms shall conform to the electrical interface conditions and requirements defined in the specification.

e) Physical interfaces

The mass of a mechanism shall conform to the requirements defined in the specification.

f) Other interfaces

Mechanisms shall conform to the interface conditions of optical (visual field), mounting alignment, accessibility during operation, envelope area, clearance with other equipment and ground-based equipment defined in the specification.

5.2 Environmental design

5.2.1 General

Mechanisms shall conform to the environmental condition requirements defined in the specification.

5.2.2 Ground environment

a) Mechanisms shall meet the required performance even under ground handling environment conditions such as ground test, assembly, storage and transportation.

b) Mechanisms shall be designed to take into account the ground test environment including temperature, vibration, sound, shock, different atmospheric gases, pressure, humidity, cleanness and corrosive environment.

5.2.3 Launch vehicle flight environment

a) Mechanisms shall meet the required performance after being exposed to launch vehicle flight environment conditions.

b) As to the launching environment, mechanisms shall be designed to take into account changes in the parameters such as temperature, vibration, sound, shock, pressure and humidity.

5.2.4 Orbital environment

a) Mechanisms shall meet the required performance under orbital environment conditions until the end of their required operating life is reached.

b) As to the orbital environment, mechanisms shall be designed to take into account environmental factors such as vacuum, temperature cycle, vibration, shock, radiation, ultraviolet and atomic oxygen. Mechanisms shall be designed to take into account the environmental effects in outer space on the materials used in the mechanism.

5.3 Parts and materials

5.3.1 General

The parts, materials and processes of the mechanism shall be selected to meet the requirements about function, performance, environmental conditions, quality, reliability, and other properties specified in the mechanism specification.

5.3.2 Requirements for parts

a) Parts used in mechanisms shall be selected from customer approved standard parts or registered parts for project use if possible and proper.

2) Parts used in mechanisms shall be selected to conform to the mechanism requirements.

3) Parts used in mechanisms shall be standardized to the possible and proper level.

5.3.3 Requirements for materials

a) Mechanism materials shall be selected to conform to the mechanism requirements specification, referring to material outgassing data, metallic materials mechanical properties data, and non-metallic materials mechanical properties data for aerospace use.

NOTE MMPDS Handbook Metallic Materials Properties Development and Standardization Handbook, MIL-HDBK-17 Composite Materials Handbook, and Aerospace Structure Metals Handbook are known as popular mechanical properties data for metallic or non-metallic materials used in aerospace industries.

b) In addition to physical and mechanical properties, corrosion resistance, galvanic corrosion resistance, susceptibility for stress corrosion cracking, and surface modification treatment (as needed) shall be taken into account in metallic materials selection.

c) Mechanism materials which are to be exposed to the outer space environment shall be selected to conform to the applicable mission requirements, to have durability for radiation, ultraviolet, atomic oxygen, and space debris, and to have low outgassing characteristics.

d) Materials shall be selected so that material property change due to temperature change and temperature cycle conforms to the mechanism requirement specification.

e) If environmental factors such as radiation, ultraviolet, atomic oxygen and temperature environment can have combined effects on the materials, materials shall be selected so that the combined effects on the materials under such complex environment conform to the mechanism requirements specification.

f) When using hygroscopic or swellable materials, materials shall be selected so that the material property change due to moisture absorption and swelling conform to the mechanism requirements specification.

5.4 Mechanism design

5.4.1 Accuracy control design

For mechanisms used in pointing application where accuracy control is necessary, the performance error due to the following factors shall be properly considered in determining the error budget:

a) machining and assembly tolerances, misalignment;

b) bending (deflection), torsion;

c) dynamic loads;

d) thermal distortion;

e) mechanical interference (movable envelope);

f) friction, friction noise (friction or torque variations), and friction hysteresis;

g) variation in driving force (driving motor ripple, spring, electromagnetic solenoid);

h) control system transient (resonance, overshoot);

i) steady-state errors;

j) other error variations (Structural and mechanical hysteresis, backlash, drive motor ripple, quantization errors in command and feedback sensors, and any other defined error source).

5.4.2 Driving capability design

A proper margin (allowance) shall be provided to mechanisms with a driven section. The following items shall be considered at the driving capability design of mechanisms:

a) For frictional forces, not only dynamic friction force during steady drive but also to static friction force and hysteresis during activation and inverse driving shall be considered.

b) For motor driving, each motor shall have a torque (or force) margin which meets the requirements for expected changes in operational temperature and speed. The driving current shall be in agreement with the power resource.

c) In reviewing (calculating) the required driving force (drive resistance), the worst-case combination of operationally expected changes in temperature and speed shall be reviewed with respect to each resistance element (such as bearing, gears, harness cables, latches and dampers). If necessary, the calculated values shall be checked for validity through testing at the element and subassembly level.

d) For drive mechanism elements using a redundant system, a proper torque (or force) margin shall be ensured in case an element fails under the worst-case conditions.

e) For deteriorated drive mechanism elements with a redundant system, the margin of other mechanism elements shall be evaluated in consideration of the possibility that the deteriorated mechanism will develop resistance force.

NOTE See Annex A for additional notes.

5.4.3 Design life

The design life of a mechanism shall correspond to the expected sum total of nominal ground test and orbital operation. Mechanism shall be designed to meet the specified life requirements under the expected environment conditions.

NOTE The specified life requirements include the margins specifically to address assembly, integration, test, and number required cycles in the life cycle of mechanisms.

5.4.4 Tribology

a) Mechanisms shall be designed to allocate dimension and dimensional tolerance to each element properly. Material and lubricant of mechanisms shall be selected to prevent adhesion, seizing, and biting and to reduce wear at the sliding surface and the rolling surface to conform to the mechanism performance requirements throughout the required lifetime.

b) Requirements to the design, storage, handling and operation of the mechanism shall be clarified in order to maintain the integrity such as prevention of the lubricating surface contamination of the mechanism.

c) The outgassing rate of the lubricant used to lubricate the mechanism shall be measured in accordance with a predetermined measurement method. Allowable outgas limit shall be determined by the applied contamination and cleanliness control requirements for space systems.

NOTE 1 See ASTM E 595 - 15.

NOTE 2 Specific requirements for mission involving advanced optical instruments are covered by the specific mechanism specification.

5.4.5 Major mechanical components

When designing mechanisms that use bearings, gears, pyrotechnic devices, springs, and so on, the appropriate design guidelines regarding these components should be referenced.

For the mechanism design that use pyrotechnic devices, ISO 26871 can be referenced to design the mechanisms.

5.4.6 Other requirements

5.4.6.1 Replaceable mechanism

Replaceable mechanisms shall be designed to ensure they can only be installed in the correct direction with consideration to mitigate human error.

5.4.6.2 Latching

Latching mechanisms shall be designed properly to prevent accidental release caused by vibration or shock generated during mission.

5.4.6.3 End stops

Mechanisms with restricted travel or rotation shall be provided with regular or emergency mechanical end stops to limit their motion and travel extremes to maximum position specified in the mechanism requirements specification.

End stops shall be provided to prevent interference with interfacing equipment.

5.4.6.4 Separable contact surface

a) Separable contact surfaces shall be designed to maintain adhesive forces between bonding surfaces below the specified limit.

b) The contact between the mating surfaces shall be designed considering surface roughness, hardness, material properties, and contact geometry.

5.4.6.5 Clearance

The proximity of the moving mechanism shall be designed without thermal blankets, tape, and electrical harnesses that may reduce or eliminate clearances, impeding the motion of mechanism. If the use of those materials is indispensable to the mechanism due to functional requirements, sufficient clearance shall be provided to prevent movable and actuating element from contacting with thermal blankets, tape, and electrical harnesses.

5.4.6.6 Venting

a) Unless the mechanism is hermetically sealed or sized in all its functions and performances for internal pressure build-up, all closed cavities shall be provided with a venting hole sized according to the launch ascent depressurisation profile.

b) The method and design of venting shall prevent particles contamination of bearings, optics and external sensitive components agreed by the customer.

c) If venting to the outside of a lubricated enclosure is implemented, the lubricant shall have compatibility with the other spacecraft materials used and conform to contamination requirements specified in the mechanism requirements specification.

5.4.6.7 Retention and release devices with pyrotechnic or other actuators

The operation of retention and release devices shall conform to the cleanness requirements applied to the individual space programs and space debris mitigation requirements specified in ISO 24113. The retention and release device shall be designed with a proper method for trapping debris.

5.5 Structural design

5.5.1 General requirements related to structural design

The structural design of a mechanism shall conform to the applicable requirements for the individual space program.

Mechanisms shall be provided with the required functions and performance under the expected thermal environment conditions throughout their entire operating life. Transitional conditions shall be included in the thermal environment conditions.

5.5.2 Allowable mechanical properties of structural materials

a) Acceptable criteria for metallic material strength allowable properties shall be based on the requirements stated in ISO 10786.

   NOTE Allowable mechanical properties for structural metallic materials are generally specified in MMPDS, Metallic Materials Properties Development and Standardization Handbook.

b) In special circumstances where design data at the required statistical level are not established, engineering evaluation or limited data acquisition tests to establish design allowable properties may be conducted per specified requirements.

5.5.3 Margin of safety

a) Mechanisms shall meet the mechanical interface and performance requirements and withstand the expected loading conditions induced by the encountered environments during handling, transportation, test, storage, launch and orbital operations without damage or deterioration.

b) Mechanisms shall have a positive margin of safety for all environmental and operational loading conditions.

5.5.4 Stiffness design

Mechanisms shall possess adequate stiffness to conform the mechanism requirements specification, especially for the case that there are requirements for natural frequencies of the mechanisms to prevent dynamic coupling with major excitation frequencies of the launch vehicle, and/or to avoid dynamic coupling of flexible modes with the spacecraft during in-orbit operations.

5.6 Thermal design

Mechanisms shall possess the required functions and performance under the expected thermal environment conditions throughout the entire lifetime. Transients shall be included in the thermal environment conditions.

5.7 Electrical design

5.7.1 Electrical design

Mechanisms shall be designed to meet the requirements for electrical performance and have stable electrical characteristics throughout the lifetime. In general, the standards specified in the mechanism specification is applied to the electric design.

5.7.2 Electrical wires

a) Wire clamps shall be used for portions where electrical wires are likely to be affected by bending.

b) Cables and electric wires shall be formed, arranged and supported considering the following items.

   1) No electric wires, electric wire terminals or connectors shall be subject to mechanical stress exceeding allowable limit.

   2) Wiring shall provide a safe distance from sharp edges or liquid pipelines.

   3) Damages and failures of cables and electric wires shall be prevented in vibration environments.

5.7.3 Electric connectors

Connector types and shapes (e.g. number of pins) shall be selected to avoid damage or connector mis-mating.

5.7.4 Insulation

The insulation of electric wires shall be designed in accordance with the standards specified in the mechanism specification.

5.7.5 Grounding

Mechanisms shall be grounded at a mechanical interface point specified in the interface control document. Any components insulated from mechanical interface points shall be grounded separately as needed.

5.7.6 Deformation of wiring

For electric wires which deform at movable portions, special consideration shall be given to possess repeatability of the shape change and reaction force of electrical wires.

5.8 General requirements

5.8.1 Safety

a) In designing a mechanism, adequate consideration should be given to safety to prevent mishaps to personnel and peripheral equipment in all phases including manufacturing, assembly, testing and transportation. Adequate consideration should be given to prevent damage to the mechanism in all the phases.

b) Safety design shall be implemented in accordance with the standards specified in the mechanism specification.

5.8.2 Dependability

a) Mechanisms are significant components which may become a single point of failure in many cases. Adequate consideration should be given to their dependability.

b) The dependability of mechanisms can be increased by providing a large design margin, decreasing the sensitivity to each parameter, or designing single points of failure with redundancy.

c) For mechanisms that are indispensable to the mission success of the space system, the required dependability shall be demonstrated by analysis or testing, according to the mechanism specification.

d) For parts with a limited operating life, the operating life shall be verified through testing or analysis.

e) A single part failure shall not cause non-conformance of other equipment or mechanisms.

f) Dependability analysis shall be performed in accordance with ISO 23460 or the standards specified in the mechanism specification.

5.8.3 Quality assurance

Documentation and data control shall be performed in accordance with ISO 27025.

5.8.4 Configuration

Parts and materials which consist of a mechanism shall be identified by function and characteristics and shall be listed. Documentation of listed parts and materials shall be maintained up to date in accordance with ISO 21886.

5.8.5 Redundancy

a) All single points of failure in the mechanism shall be identified in the design phase. To minimize the number of single points of failure and meet the reliability requirements, the mechanism shall be designed with a redundant configuration where possible.

b) If the entire mechanism cannot be designed with a redundant configuration, redundancy shall be considered at the mechanism component level.

c) In the redundant system, the system shall be designed not to lose the specified functions and performances if one redundant component interferes with another redundant component.

d) Failure of one component in the redundant system shall not cause non-conformance of functions or parts in another redundant component.

5.8.6 Operability

a) No operational restrictions shall be imposed on the mission of the system in designing a mechanism. If imposing operational restrictions is inevitable, the conditions of the operational restrictions shall be identified.

b) When off-nominal operational requirements are demanded by the system, a worst-case analysis under off-nominal operation shall be implemented and shall support the system design to minimize the sensitivity of operational performance to the changes of parameters.

5.8.7 Maintainability

a) Mechanisms shall be designed to be maintenance-free during storage or ground operation. If maintenance is required during storage or at the end of the ground operating life, adequacy of the maintenance shall be ensured by the records concerning the number of operation cycles, non-conformance identification and repair details.

b) Mechanisms should be designed to be able to replace critical parts if appropriate.

5.8.8 Interchangeability

Mechanisms and parts shall be designed to possess interchangeability where possible.

5.8.9 Fool-proof design

a) Mechanisms and parts shall be designed to prevent improper assembly due to human errors.

b) Mechanisms and parts shall be designed so that testing and inspections can be implemented to check for proper assembly and mounting.

5.8.10 Other requirements

5.8.10.1 Identification nameplate

a) Mechanisms and parts shall be identified by nameplates. Nameplates shall be attached to an outer surface so that no mechanism functions will be affected.

b) Labelling, etching or marking with regard to the article may be performed if there are no appropriate outer surfaces to which to attach a nameplate.

5.8.10.2 Non-flight identification

Non-flight articles shall be identified from flight articles.

5.8.10.3 Measurement items

a) Mechanisms shall be designed so that important data which can ensure its performance and identify anomalies in case of failures will be measured continually from the verification testing phase on ground to the in-orbit operation phase.

b) Measurement data shall be obtained through a telemeter wherever possible.

6 Verification

6.1 General

a) The development of space mechanisms shall include a verification process in conformance with ISO 23135[1)]. Verification can be performed by the result of test, analysis, demonstration (e.g. similarity), inspection or a combination of those.

NOTE The mechanisms verification requirements are subdivided into analytical and test verification requirements.

b) A verification matrix shall be established by the supplier and provided to the customer for obtaining concurrence.

6.2 Verification by analysis

6.2.1 General

6.2.1.1 Analytical verification items of mechanisms

Analytical verification of mechanisms shall include the following tasks:

a) thermal analysis (identification of the worst operational and non-operational cases);

b) structural analysis (stiffness, stress and fatigue caused by mechanical/thermal loads);

c) performance analysis of operable functions under all applicable environments and operational conditions (based on the worst-case conditions identified) in order to derive the load, time, shock, speed, dimensional stability and position accuracy;

d) torque/force margin;

1) Under preparation. Stage at the time of publication: ISO/FDIS 23135:2022.

e) occurrence of shock and sensitivity;

f) occurrence of external disturbance and sensitivity;

g) lubrication analysis;

h) life analysis;

i) magnetic or electromagnetic analysis;

j) radiation analysis;

k) stress analysis.

6.2.1.2 Models and simulations (M&S)

Models and simulations (M&S) which are applied to the analyses performing for the mechanism product verification and validation (V&V) shall be documented, verified and validated to reduce the risks associated with the credibility of M&S results.

NOTE See Annex C for best practices of models and simulations (M&S).

6.2.2 Identification of worst-case conditions

The operational and non-operational conditions under the mechanism worst-case conditions shall be set in accordance with the environments and loads, for specific spacecraft and mechanisms, and those functional performances.

6.2.3 Thermal analysis

Thermal analysis of mechanisms shall conform to the requirements specified in the standards specified in the mechanism specification.

6.2.4 Structural analysis

Structural analysis of mechanisms shall conform to the requirements specified in ISO 10786.

6.2.5 Function and performance analysis

The requirements for functional models are listed as follows.

a) The analytical models or numerical models to be used as the basis of analysis shall represent the characteristics of the mechanism with respect to the following items; interface conditions and spacecraft characteristics shall be also included in those characteristics:

    1) mass;

    2) inertial force;

    3) position of centre of gravity;

    4) structural stiffness;

    5) applied force or applied torque;

    6) resistant force.

b) The following items shall be performed on the model shown in a):

    1) parametric study of mechanical variation factors shall be implemented;

    2) the analytical model shall be updated through the design and test phases if necessary.

The analysis results shall be verified in comparison with the related test results.

6.2.6 Analysis of torque/force margin

The conformity of the mechanisms to the specified requirements related to the torque/force margin shall be verified by analysis.

NOTE See Annex A for additional notes.

6.2.7 Shock generation and susceptibility

The conformity of the mechanism to the requirements for shock generation and susceptibility specified in the mechanism requirements specification shall be verified by analysis.

6.2.8 Generated disturbance

The operation of mechanisms shall be verified by analysis using parameters representative of the flight configuration, to conform to the induced loads-related requirements (e.g. micro-vibration) defined in the mechanism requirements specification.

The rotational or moving parts of the mechanism shall be balanced to conform the specified requirements on disturbances.

6.2.9 Lubrication analysis

a) The selection of the lubrication system shall be evaluated to conform to the application method or operating life specified in the mechanism requirements specification.

b) The adequacy of lubricant quantity shall be evaluated by analysis.

6.2.10 Life analysis

a) Mechanical parts with a limited operating life shall be identified.

b) Mechanical parts with a limited operating life shall be verified to conform to the operating life requirements specified in the mechanism requirements specification.

NOTE See the minimum lifetime factors stated in Annex B in addition to the scatter factor specified in ISO 10786.

6.2.11 Magnetic or electromagnetic analysis

The compatibility of the EMC requirements shall be verified by analysis. EMC analysis shall be performed in accordance with ISO 14302.

6.2.12 Radiation analysis

Radiation-sensitive components for total ionizing doses shall be analysed to verify that the mechanisms conform to the performance requirements including operating life. Radiation analysis shall be performed in accordance with the standards specified in the mechanism specification.

6.2.13 Electrical parts stress analysis

Stress analysis on electric parts (including harnesses) shall be implemented to verify that the electric parts conform to the derating requirements. The derating analysis of power wire harness shall be performed in accordance with the standards concerning wire derating specified in the mechanism specification.

6.3 Verification by test

6.3.1 General

a) In tests, the hardware shall be verified to conform to the requirements related to design, manufacturing and performance. Testing includes development tests, qualification tests, acceptance tests and operating life tests.

b) The mechanism design shall adapt to the ground operation under atmospheric environment conditions and thermal vacuum conditions. Allowable operations and/or restrictions on operations under the expected environmental conditions shall be defined.

c) The mechanism design shall be implemented with consideration given to conducting typical ground tests in operational configurations of mechanisms. The mechanism design shall adapt to testing under the atmospheric environment and thermal vacuum environment conditions under gravity.

d) Verification testing shall be planned and performed in consistency with the requirement stated in ISO 15864.

6.3.2 Development tests

a) Planning

Development tests shall be planned and conducted as follows:

1) input necessary to design and analysis (especially for dynamic analysis) for flight articles shall be acquired by development tests;

2) new designs shall be verified through development tests;

3) verification of the critical mechanisms shall be implemented through development tests.

b) Tests

Unless clearly verified based on the test data obtained from the past space application cases, the following tests shall be conducted by the engineering model of the mechanisms in the initial phase of the project:

1) functional performance tests;

2) vibration test and shock test (if necessary, as verification of new design);

3) thermal vacuum test or temperature test (if necessary, as verification of new design);

4) life test on life critical components.

c) Identification of test articles

Critical mechanisms and parts which require a development test shall be identified in the initial phase of the design and development program.

6.3.3 Qualification tests

6.3.3.1 General

All mechanisms shall be qualified by test for application in which they are used.

The qualification tests shall be conducted in a representative sequence and in a representative environment.

6.3.3.2 Vibration, acoustic and shock tests

Vibration, acoustic and shock tests shall be performed in accordance with the structure-related requirements specified in ISO 10786 and ISO 15864.

6.3.3.3 Thermal vacuum test

The thermal vacuum test shall be performed in accordance with the requirements specified in ISO 15864.

6.3.3.4 Functional test

The functional test shall verify that the mechanisms conform to the function and performance requirements following exposure to environmental conditions (loads, thermal) at qualification level and mechanism qualification duration.

Mechanical settling and thermal stabilization shall be performed prior to functional tests.

6.3.3.5 EMC test

When using an EMC-sensitive component with regard to the mechanism or when spacecraft-specific EMC requirements are imposed on the mechanism, the electromagnetic interference characteristics (emission and susceptibility) of the mechanism shall be verified. EMC test shall be performed in accordance with ISO 14302 and ISO 15864.

6.3.3.6 Electrical test

An electrical test shall verify that the mechanism conforms to the electrical function and performance requirements.

6.3.4 Acceptance tests

6.3.4.1 General

For products newly assembled based on the qualified design, acceptance tests shall be conducted to demonstrate the conformance to mechanism requirements specification and to provide quality-control assurance against workmanship or manufacturing deficiencies. Acceptance tests shall be conducted at a level higher than the expected level in the flight phase but lower than the qualification test level. Testing shall be conducted at a level which causes no detrimental damage to the hardware. No adjustments or repair shall be made on mechanisms during acceptance testing or after completion of testing except in the case of necessary refurbishment, such as separation devices, pyrotechnic devices.

6.3.4.2 Test description

Acceptance testing should include the following criteria, in addition to the detection of workmanship errors or manufacturing deficiencies.

a) The functions and performance shall conform to the requirements.

b) The electric wiring shall be verified to withstand the required voltage without causing destructive discharge.

6.3.4.3 Run-in

Run-in should be performed on mechanisms, unless it can be shown that this procedure would be detrimental to performance and would result in reduced reliability.

6.3.4.4 Inspection

The dimensions, mass, appearance and identification marking of the mechanisms shall be inspected properly after the acceptance testing.

6.3.5 Life test

6.3.5.1 Operating life qualification

The design, operating life and performance of mechanisms shall be verified by test on the designated test article equivalent to the flight article, in the operating life test conditions simulating the ground and in-orbit environment conditions after exposure to the environmental tests of which level is higher than of the acceptance test.

6.3.5.2 Requirements for operating life test conditions

The operating life test conditions shall properly represent the following parameters which impact the operating life.

a) Thermal conditions, load conditions and motion profiles properly corresponding to operational conditions.

b) When conducting an accelerated operating life test to verify the operating life performance of a mechanism, test condition shall be defined so that accelerating temperature and/or speed does not change the failure mode of a mechanism.

NOTE See Annex B for life test duration factors.

6.3.5.3 Acceptance criterion of operating life test

In an operating life test, the functional performance of mechanisms shall conform to the design requirements after the test.

Annex A
(informative)

Driving capability design (torque/force margin)

A.1 General

Current existing space-flight mechanism-related standards[5]-[7],[9] have different quantitative requirements concerning torque/force margins applied to the driving capability design. The customer needs to define the requirements for torque/force margins in the mechanism specifications.

This annex provides information concerning torque and force margins specified in the existing standards[1]-[3],[5] and a comparison among those standards.

A.2 Functional dimensioning (motorization)[7]

Reference [7] defines motorization factors and actuation torque or force as follows.

a) Motorization factors

Torque or force contributors providing help to torques or forces are treated as motorization.

Actuators (electrical, mechanical, or thermal) are sized to provide throughout the operational lifetime and over the full range of travel actuation torques or forces in conformance with Formula (A.1) or Formula (A.2).

To derive the factored worst-case resistive torques or forces, each contributor, considering all mission phases worst-case conditions (environmental effects such as vacuum, temperature and zero-gravity), is multiplied by the applicable minimum uncertainty factor specified in Table A.1.

NOTE 1 Increased factors are typically applied to take into account effects that cannot be measured by test.

Table A.1 — Minimum uncertainty factors for actuation function

Resistive torque or force contributors	Symbol	Theoretical factor	Measured factor
Inertia	I	1,1	1,1
Spring	S	1,2	1,2
Magnetic effects	H_M	1,5	1,2
Friction	F_R	3	1,5
Hysteresis	H_Y	3	1,5
Others (e.g. harness)	H_A	3	1,5
Adhesion	H_D	3	3

The theoretical uncertainty factors in Table A.1 may be reduced to the measured factors, provided that the worst-case resistive contributors are based on measurements, according to a test procedure approved by the customer.

The minimum actuation torque (T_{min}) is derived by Formula (A.1):

$$T_{min} = 2 \times (1{,}1I + 1{,}2S + 1{,}5H_M + 3F_R + 3H_Y + 3H_A + 3H_D) + 1{,}25T_D + T_L \quad (A.1)$$

where

I is the resistive inertial torque applied to a mechanism subjected to acceleration in an inertial frame of reference (e.g. spinning spacecraft, payload or other);

T_D is the inertial resistance torque caused by the worst-case acceleration function specified by the customer at the mechanism level;

T_L is the deliverable output torque, when specified by the customer.

The minimum actuation force (F_{min}) is derived by Formula (A.2):

$$F_{min} = 2 \times (1,1I + 1,2S + 1,5H_M + 3F_R + 3H_Y + 3H_A + 3H_D) + 1,25F_D + F_L \quad (A.2)$$

where

I is the inertial force applied to a mechanism subjected to acceleration in an inertial frame of reference (e.g. spinning spacecraft, payload or other);

F_D is the inertial resistance force caused by the worst-case acceleration function specified by the customer at the mechanism level;

F_L is the deliverable output force, when specified by the customer.

NOTE 2 Margins against any dynamic coupling between the mechanism and its payload are not covered by Formulae (A.1) and (A.2); and they are addressed on a case by case basis when appropriate.

b) Actuation torque (or force) dimensioning.

1) Torque T or force F is greater or equal than T_{min} or F_{min} respectively as calculated in Formulae (A.1) and (A.2).

2) When the actuation torque or force is supplied by an electrically controlled device, the actuation torque or force supplied by this device is derived considering worst-case conditions.

NOTE 1 Example of such electrical devices are an electromagnetic motor, piezo actuator, pneumatic, or smart materials.

NOTE 2 Example of such worst-case conditions are supplied voltage, current, and frequency.

3) When part of the actuation torque or force is provided by inertia means, the actuation torque or force supplied by the inertia is:

i) derived considering worst-case conditions defined and agreed by the customer;

ii) multiplied by the maximum uncertainty factor of 0,9 and then conforming to the Formulae (A.1) and (A.2).

NOTE 3 Inertia is calculated in the appropriate reference frame and according to the type of movement.

NOTE 4 An example of inertia actuating torques or forces is deployment from a spinning spacecraft.

4) When the actuation torque or force is supplied by a spring actuator, the actuation torque or force supplied by the spring, is:

i) derived considering worst-case conditions;

ii) multiplied by the maximum uncertainty factor of 0,8 when ageing measurement are not available; and

iii) agreed with customer when ageing measurement are performed.

5) Spring actuators need to be redundant unless it is

i) agreed by the customer;

ii) verified by analysis and test that the spring sizing and functional performance characteristics meet the specified reliability of the mission; and

iii) verified that a spring failure cannot cause any catastrophic, critical or major hazardous event in conformance with applicable safety requirements (see ECSS-Q-ST-40C Rev.1:2017, Clause 6.4).

6) Actuating torques or forces based on hysteresis, harness generated, or any item whose primary function is not to provide torques or forces, is designed not to be used as a motorization source.

7) If torques (or forces) are based on hysteresis, harness generated, or any item whose primary function is not to provide torques or forces are used as motorization sources, their use are:

i) justified;

ii) agreed by the customer; and

iii) subject to the verification by analysis and test of the adequacy of the uncertainty factor with respect to the dispersion of the actuation torque or forces.

8) When the actuation torque or force is supplied by an electric motor, the worst-case torque or force generated by the motor is based on:

i) measurement at operating conditions; or

ii) agreement with the customer if a measurement is not available.

NOTE 5 Operating conditions include speed and duty cycle.

c) Holding torque or force dimensioning

1) For safety critical mechanisms in crewed space missions, the holding torque or force is designed to be sized to provide 2 times the torques or forces applied by operational or environmental design limit loads under worst-case conditions and throughout the operational lifetime.

NOTE 6 The holding function prevents motion and inadvertent operation of a mechanism by providing torque or force using powered or unpowered means.

2) For safety critical mechanisms in crewed space missions, minimum uncertainty factors for torque or force are applied in conformance with Table A.2 according to the following rules:

i) for torque or force contributors that help the holding function, divide the worst-case value by the uncertainty factor;

ii) for torque of force contributors that prevents the holding function, multiply the worst-case value by the uncertainty factor.

Table A.2 — Minimum uncertainty factors for holding function

Torque of force contributors	Theoretical factor	Measured factor
Inertia	1,1	1,1
Spring	1,2	1,1
Magnetic effects	1,5	1,1
Friction	3	1,5

Table A.2 *(continued)*

Torque of force contributors	Theoretical factor	Measured factor
Hysteresis	3	1,5
Others (harness)	3	1,5
Adhesion	3	3

A.3 Torque and force margins[6]

In Reference [6], torque margin is defined as follows:

$$M_{\text{trq}} = \frac{T_{\text{avail}}}{\sum K_{\text{f}} T_{\text{f}} + \sum K_{\text{v}} T_{\text{v}}} - 1 \tag{A.3}$$

where

M_{trq} is the torque margin;

T_{avail} is the minimum available torque generated by the mechanism at worst-case environmental conditions at any time in its life;

T_{f} is the individual fixed resistive torque that is well-known and not strongly influenced by friction, temperature, life, or other highly variable phenomena;

T_{v} is the individual resistive torques that may vary over environmental conditions and life;

K_{f} and K_{v} are factors applied to each individual resistive torque prior to summation per Table A.3.

Table A.3 — Minimum torque/force margin factors

Origin of factor	K_{f}	K_{v}
Value obtained via theory or analysis	1,5	3,0
Value obtained via test of flight-like hardware	1,25	2,0
Value for one-spring-out case[a]	1,0	1,0
[a] Spring-driven mechanisms that utilize multiple springs nominally working together to provide torque may utilize a minimum K_{f} and K_{v} of 1,0 for the cases in which one of those springs fails. Prior to failure, the nominal (nonfailure) factors still apply.		

For linear devices, "force" replaces "torque" in Formula (A.3) and its descriptions. T_{avail} represents torques from actuators such as motors, springs, pyrotechnics, solenoids, heat actuated devices, and other devices. Examples of fixed torques, represented by T_{f}, include accelerated inertias, motor detent torques, and unbalanced pressure loads limited by relief mechanisms; all other resistive torques tend to be variable enough that a higher factor is more appropriate and thus fall under T_{v}. Examples include static or dynamic friction, alignment effects, wire harness torques, damper drag, and variations in lubricant effectiveness, including degradation or depletion of lubricant over life.

Formula (A.3) can be used to calculate holding torque margin, starting torque margin, dynamic torque margin, and pull-in torque margin (for stepper motors).

For holding torque margin, T_{avail} is the actuator torque; while T_{f} and T_{v} are the torques that tend to disturb the mechanism.

For starting torque margin, T_{avail} is the actuator torque; while T_{f} and T_{v} are the resistive torques.

For dynamic torque margin, T_{f} is the torque required to accelerate an inertia by a given amount; and T_{v} is the resistive torque.

For pull-in torque margin, T_{avail} is the pull-in torque at a given drive rate; T_f is the maximum detent torque; and T_v is the total friction torque seen by the motor.

All calculated force and torque margins account for worst-case credible combinations of factors at end of life.

Because spacecraft mechanisms are exposed to many factors in combination that can deplete margin, calculation of force and torque margins also account for these factors in combination. The following considerations should be included in margin calculations as they reflect phenomena that are frequently found to cause problems in margin calculation:

— environmental conditions;

— frictional effects;

— possible changes in static and dynamic friction due to storage time;

— alignment effects;

— wire harness loads;

— damper drag;

— thermally induced distortions;

— load-induced distortions;

— variations in lubricity;

— fluid pressure on the elastomers in viscous dampers;

— supply voltage, motor, and controller parameters;

— acceleration due to vehicle motion or manoeuvres that can retard motion;

— loading due to vibroacoustic environment.

A positive torque or force margin ensures that the mechanism retains reserve torque or force that can be applied in the event of an unforeseen effect that robs motive force from the mechanism.

The torque margins are calculated at the motor output because the resistive torques present in the gear heads can drive the minimum margin to be at the motor output rather than at the gear head output. Basing torque margin on the gear head output can give a false impression of the true torque margin.

All torque and force margins are verified during an acceptance test at the highest possible level of assembly.

A.4 Force/Torque margins[5]

In Reference [5], the following two components of margin are considered:

— the static torque or force margin that applies to the torque or force required to overcome drive resistance;

— the dynamic margin that applies to the torque or force required to impart acceleration.

Minimum available driving capability and maximum load determination are verified by test and analysis; each element of resistance is characterized in this test program.

In spring-driven mechanisms where redundant springs are used instead of a backup deployment mechanism, the mechanism have a positive torque or force margin for a one-spring-out case based on combining worst-case conditions. The moving mechanical assembly (MMA) is designed such that the resistive forces or torques as a result of broken springs are minimized.

a) Static torque or force margin

The static torque margin is defined as the ratio of the drive torque available divided by the resisting torque (torque required to overcome friction, wire harness bending, etc.), minus one.

The static torque margin is expressed in percentage and is calculated as given in Formula (A.4):

$$M_{\mathrm{trq,S}} = \frac{T_{\mathrm{drive}}}{T_{\mathrm{resisting}}} - 1 \qquad \text{(A.4)}$$

where

$M_{\mathrm{trq,S}}$ is the static torque margin;

T_{drive} is the driving torque;

$T_{\mathrm{resisting}}$ is the resisting torque.

For linear devices, “force” replaces “torque.”

Static torque or force margin is at least 100 % at any position of motion. For new designs, the margins in Table A.4 are used. For those systems where the observed values of the driving and resisting torques or forces are extremely low, poorly characterized, or highly variable, higher margins than those specified in Table A.4 are used.

Table A.4 — Minimum recommended static torque or force margin for new designs

Design phase	Force or torque margin
Conceptual design review	1,75
Preliminary design review	1,50
Critical design review	1,25
Acceptance/Qualification test	1,00

b) Dynamic torque margin

The dynamic torque margin is defined as the ratio of the drive torque minus resisting torque (torque required to overcome friction, wire harness bending, etc.) divided by the torque required for acceleration, minus one.

The dynamic torque margin is expressed in percentage and is calculated as as given in Formula (A.5):

$$M_{\mathrm{trq,D}} = \frac{T_{\mathrm{drive}} - T_{\mathrm{resisting}}}{T_{\mathrm{accel}}} - 1 \qquad \text{(A.5)}$$

where

$M_{\mathrm{trq,D}}$ is the dynamic torque margin;

T_{drive} is the driving torque;

$T_{\mathrm{resisting}}$ is the resisting torque;

T_{accel} is the torque required for acceleration.

For linear devices, “force” replaces “torque.”

The dynamic torque or force margin is calculated by using the minimum drive capability available to accelerate a specified inertia or mass at a specified rate. Acceleration due to vehicle motion or manoeuvres which can retard deployment is included as part of the required acceleration. The dynamic torque or force margin, where practical, is designed to be greater than 25 % at any position of motion.

A.5 Static/Dynamic torque margin[9]

In driving mechanisms, drive torque of actuator considers two components of margin: the static torque margin and the dynamic torque margin.

The static torque margin is defined as the ratio of the drive torque less the torque required for acceleration divided by the resisting torque (torque required to overcome friction and other resistant elements), minus one.

The static torque margin is calculated as given in Formula (A.6) and is designed to be greater than one.

$$M_{trq,S} = \frac{T_{drive} - T_{accel}}{T_{resisting}} - 1 \geq 1 \tag{A.6}$$

where

$M_{trq,S}$	is the static torque margin;
T_{drive}	is the driving torque;
$T_{resisting}$	is the resisting torque;
T_{accel}	is the torque required for acceleration.

The dynamic torque margin is defined as the ratio of the drive torque less the resisting torque (torque required to overcome friction and other resistant elements) divided by the torque required for acceleration, minus one.

The dynamic torque margin is calculated as given in Formula (A.7) and is designed to be greater than 0,25.

$$M_{trq,D} = \frac{T_{drive} - T_{resisting}}{T_{accel}} - 1 \geq 0{,}25 \tag{A.7}$$

where, $M_{trq,D}$ is the dynamic torque margin.

If it is not appropriate for a driving mechanism to calculate torque margin by the above method or to apply another method i.e. energy method to calculate torque margin, design validity is assessed by each program.

The following statements are considered for the resisting torque and the drive torque.

a) For friction torques, not only dynamic friction torque during steady drive but also static friction torque and hysteresis during activation are considered.

b) For motor drive, each motor is designed to have a torque margin which meets the requirements for expected changes in operational temperature and speed. The driving current is designed to be within the limit of the power resource.

c) When estimating the resisting torque, the worst-case combination of operational temperature and revolution speed are considered with respect to each resistant element (such as bearing, gears, harness cables, latches and dampers). If necessary, the calculated values are verified through element and subassembly level test.

d) For drive mechanism element with redundant system, adequate torque margin is ensured in case one element fails under the worst-case conditions.

e) For degradation of drive mechanism with redundant mechanism, the torque margin of remaining mechanism element is evaluated in consideration that the degraded mechanism element causes resistant torque.

"Torque" is replaced with "force", if driving form is not revolution.

A.6 Comparisons of the torque/force margin requirements in existing standards

The customer defines the requirements for torque/force margins in the mechanism specifications.

The requirements concerning torque/force margins in the existing standards are expressed by different expressions, so that the comparisons of the torque/force margin requirements in existing standards are difficult in original definitions.

Table A.5 shows comparisons of the torque/force margin requirements in existing standards.

To ease the comparisons of those existing standards, torque margins definitions in Table A.5 are expressed by common style using the parameters' expression in Reference [7].

Table A.5 — Comparisons of the torque/force margin requirements in existing standards

	Torque Margin Definition (Original)	Torque Margin Definitions using parameters' expression in Reference [3] M_{torque}: Torque margin, I:Inertia, S:Spring, H_M: Motor magnetic effects. F_R: Friction, H_Y: Hysteresis, H_A: Others (e.g. Harnesses), H_D: Adhesion, T_D: Inertial resistance torque
Reference [2]	Analysis $M_{trq} = \frac{T_{avail}}{\sum 1,5T_f + \sum 3T_v} - 1 > 0$ NOTE: The variance of $\sum 1,5T_f$ is small, and the variance of $\sum 3T_v$ is large, comparatively.	$M_{trq} = \frac{T_{avail}}{\sum 1,5T_f + \sum 3T_v} - 1 = \frac{T_{avail}}{(1,5I + 1,5S + 1,5H_M + 1,5T_D) + (3F_R + 3H_Y + 3H_A + 3H_D)} - 1 > 0$
	Test $M_{trq} = \frac{T_{avail}}{\sum 1,25T_f + \sum 2T_v} - 1 > 0$	$M_{trq} = \frac{T_{avail}}{\sum 1,25T_f + \sum 2T_v} - 1$ $= \frac{T_{avail}}{(1,25I + 1,25S + 1,25H_M + 1,25T_D) + (2F_R + 2H_Y + 2H_A + 2H_D)} - 1 > 0$
Reference [3]	Analysis $T_{min} = 2\times$ $(1,1I + 1,2S + 1,5H_M + 3F_R + 3H_Y + 3H_A + 3H_D)$ $+ 1,25T_D$ NOTE: Deliverable output torque T_L is omitted.	$M_{trq} = \frac{T_{avail}}{2\times(1,1I + 1,2S + 1,5H_M + 3F_R + 3H_Y + 3H_A + 3H_D) + 1,25T_D} - 1$ $= \frac{T_{avail}}{2\times(1,1I + 1,2S + 1,5H_M) + 1,25T_D + 2\times(3F_R + 3H_Y + 3H_A + 3H_D)} - 1 > 0$
	Test $T_{min} = 2\times$ $(1,1I + 1,2S + 1,2H_M + 1,5F_R + 1,5H_Y + 1,5H_A + 3H_D)$ $+ 1,25T_D$ NOTE: Deliverable output torque T_L is omitted.	$M_{trq} = \frac{T_{avail}}{2\times(1,1I + 1,2S + 1,2H_M + 1,5F_R + 1,5H_Y + 1,5H_A + 3H_D) + 1,25T_D} - 1$ $= \frac{T_{avail}}{2\times(1,1I + 1,2S + 1,2H_M) + 1,25T_D + 2\times(1,5F_R + 1,5H_Y + 1,5H_A + 3H_D)} - 1 > 0$
Reference [5]	Static torque margin $M_{trq,S} = \frac{T_{drive} - T_{accel}}{T_{resisting}} - 1 \geq 1$	$M_{trq,S} = \frac{T_{avail}}{2\times(I + S + H_M) + T_D + 2\times(F_R + H_Y + H_A + H_D)} - 1 > 0$ Note: In the above formula, The drive torque T_{drive}, the resisting torque $T_{resisting}$, and the torque required for acceleration T_{accel} are represented as T_{avail}, $I + S + H_M + F_R + H_Y + H_A + H_D$, and T_D, respectively.
	Dynamic torque margin $M_{trq,D} = \frac{T_{drive} - T_{resisting}}{T_{accel}} - 1 \geq 0,25$	$M_{trq,D} = \frac{T_{avail}}{(I + S + H_M) + 1,25\times T_D + (F_R + H_Y + H_A + H_D)} - 1 > 0$