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Space systems — Flywheel module design and testing

Systèmes spatiaux — Conception et essai du module de volant moteur

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Introduction

Flywheels are mechanical devices that store kinetic energy in a rotating mass. A simple example is the potter's wheel, which was widely used by people in ancient times. The first use of such devices dates from between 3500 and 3000 BC. According to archaeological evidence, these early flywheels were built from wood, stone and clay. One type of potter's wheel was a rim made from a unidirectional material (bamboo), wound in the hoop direction and embedded in a matrix (clay). This design option is clearly a foreshadowing of the later use of composites for their inherent strength and lightweight nature.

It is, however, only since the 1970s that the use of flywheels as energy storage systems has become the focus of serious attention from energy researchers due to the constant threat of a shortage of fossil fuel supplies. Today, a typical flywheel energy system consists of a flywheel rotor, a supporting device (magnetic bearing ball bearings, superconductor bearings or other types of bearings), a charge/discharge device (motor/generator) and a safety containment (housing). For space applications, due to weight constraints, the use of a bulky safety containment system is not necessarily a desirable design. Thus, from a safety point of view, the design of flywheel energy systems needs to concentrate on reliability and longevity.

Current flywheel energy storage technology is made possible by the use of high-strength, carbon-fibre-based composite materials in the rotor. Flywheel energy storage systems are designed to both control spacecraft attitude and to store energy — functions which have historically been performed by two separate systems. The stored energy is needed for the dark portions of the orbit when the Earth's shadow makes solar power unavailable for spacecraft. For many spacecraft, flywheels offer the potential to significantly reduce weight and extend service life. However, the use of composite materials, coupled with variations in design approaches and demanding operating conditions, combine to present certification challenges for the rotor assemblies.

This International Standard establishes the design, analysis, material selection and characterization, fabrication, test and inspection of the flywheel module in a flywheel. Many requirements set forth in this International Standard can also be adapted by similar types of rotating machineries, but for different usage. The momentum wheels and momentum gyroscopes are typical examples. The implementation of these requirements will ensure a high level of confidence in achieving safe operation and mission success for these critical hardware items.

Space systems — Flywheel module design and testing

1 Scope

This International Standard establishes the design, analysis, material selection and characterization, fabrication, test and inspection of the flywheel module (FM) in a flywheel used for energy storage in space systems. These requirements, when implemented on a flywheel module, will ensure a high level of confidence in achieving safe operation and mission success. With appropriate modifications, this International Standard can also be applied to similar devices, such as momentum and reaction wheels and control-moment gyroscopes.

The requirements set forth in this International Standard are the minimum requirements for flywheel modules in flywheels used in space flight applications. They are specifically applicable to the parts in the flywheel rotor assembly (FRA), including rim, hub and/or shaft and other associated rotating parts, such as the bearings and the motor generator rotor. The requirements are also relevant to the non-rotating parts, such as module housing, main suspension assembly (magnetic or rolling element bearings, superconductor bearings, etc.), motor stator, caging mechanism and sensors within the module housing, and backup bearings, if applicable. However, control and interface electronics are not covered in this International Standard.

2 Terms, definitions, symbols and abbreviated terms

2.1 Terms and definitions

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

2.1.1
A-basis allowable
mechanical strength value above which at least 99 % of the population of values is expected to fall, with a confidence level of 95 %

NOTE See also **B-basis allowable** (2.1.4).

2.1.2
acceptance tests
required formal tests conducted on hardware items to ascertain that the materials, manufacturing processes and workmanship meet specifications

2.1.3
allowable load
allowable stress
allowable strain
maximum load that can be accommodated by a structure/material without rupture, collapse or detrimental deformation in a given environment

NOTE Allowable loads commonly correspond to the statistically-based minimum ultimate strength, buckling strength and yield strength, as applicable.

2.1.4
B-basis allowable
mechanical strength value above which at least 90 % of the population of values is expected to fall, with a confidence level of 95 %

NOTE See also **A-basis allowable** (2.1.1).

2.1.5
catastrophic failure
structural failure event due to the rotor separation, or the rupture or collapse, of other flywheel rotor assembly components or assembly

2.1.6
composite material
combination of materials which differ in composition or form on a macro-scale

NOTE The constituents retain their identities in the composite, i.e. they do not dissolve or otherwise merge completely into each other, although they act in concert. Normally, the composites can be physically identified and exhibit an interface between one another.

2.1.7
damage tolerance
ability of structure/material to resist failure due to the presence of flaws for a specified period of unrepaired usage

2.1.8
damage tolerance life
required period during which a part of a flywheel module, even containing a large undetected crack, is shown by analysis or testing not to fail catastrophically in the expected service load and environment

2.1.9
damage tolerance analysis
damage tolerance testing
analysis/testing that is used to demonstrate damage tolerance life

NOTE For metallic parts, this type of analysis is also referred to as safe-life analysis.

2.1.10
design safety factor
multiplying factor to be applied to the limit load and/or maximum expected operating speed

2.1.11
fatigue life
number of load cycles experienced in service that a defect-free part in a flywheel module can sustain before failure of a specified nature could occur

NOTE The number of load cycles experienced in service can be flight loads, ground test loads and charge/discharge cycles.

2.1.12
flaw
local discontinuity in a structural material

EXAMPLE Crack, delamination, void.

2.1.13
flight-like test article
test article that is built in accordance with a fabrication process identical to the flight hardware

2.1.14
flywheel module
FM
assembly of mechanical parts which support and spin the flywheel rotor assembly and which house the appropriate sensors, rotor support systems and motor, which with the appropriate avionics suite and software can act as a stand-alone functional flywheel unit

NOTE A flywheel module typically includes the housing, main suspension system (magnetic or rolling element bearing, superconductor bearings), motor stator, caging mechanism, sensors and backup bearings, if applicable.

2.1.15
flywheel rotor assembly
FRA
assembly in a flywheel which consists of rim, shaft and/or hub, bearings, motor generator rotor and other associated parts that rotate under normal operation

2.1.16
fracture critical part
classification of a part for manned space systems, which assumes that fracture or failure of that part resulting from occurrence of a crack-like defect would create a catastrophic hazard

NOTE Such classification is required on components unless it can be shown otherwise, i.e. if the part (and subsequent parts it could fail) can be shown to be contained, or in the case of low released energy, or if the part is failsafe, or if there is only a remote possibility of significant crack growth on the part to begin with.

2.1.17
fracture control
application of design philosophy, analysis method, manufacturing technology, quality assurance and operating procedures to prevent premature structural failure caused by the propagation of cracks or crack-like flaws during fabrication, assembly, testing, transportation and ground-handling and service

2.1.18
fracture mechanics
engineering discipline that describes the behaviour of cracks or crack-like flaws in materials under stress

2.1.19
fracture toughness
generic term for measurements of resistance to extension of a crack

2.1.20
impact damage
damage in a non-metallic part within the flywheel module that is caused by an object striking the part or by the part striking an object

2.1.21
impact damage tolerance
ability of the fracture critical non-metallic parts in the flywheel module to resist strength degradation due to the impact damage event

2.1.22
initial flaw size
maximum flaw size, as defined by non-destructive evaluation, that is assumed to exist for the purpose of performing a damage tolerance (safe-life) analysis or testing

2.1.23
key process parameter
KPP
critical process parameter that affects design and product characteristics

2.1.24
life factor
factor by which the service life is multiplied to obtain total fatigue life or damage tolerance life

NOTE Life factor is often referred to as a scatter factor that is normally used to account for the scatter of a material's fatigue or crack growth rate data. It can also account for the dispersion of loading spectra parameters and other uncertainties, when appropriate.

2.1.25
limit load
maximum expected external load, or combination of loads, that a rotating part can experience during the performance of a specified mission in specified environments

NOTE When a statistical estimate is applicable, the limit load is that load not expected to be exceeded at 99 % probability with 90 % confidence.

2.1.26
margin of safety
MS
margin of safety expressed as $\left(\frac{\tau_{\text{allow}}}{\tau_{\text{limit}} \times k_{\text{safe}}}\right) - 1$

where

τ_{allow} is the allowable load;

τ_{limit} is the limit load;

k_{safe} is the design safety factor

NOTE Load can mean stress or strain (see 2.1.3).

2.1.27
maximum expected operating speed
MEOS
maximum spinning speed that a part in a flywheel module is expected to experience during its normal operation

NOTE Maximum expected operating speed is synonymous with limit speed.

2.1.28
maximum design speed
MDS
highest possible operating speed based on a combination of credible failures

NOTE Maximum design speed is required for some manned systems to accommodate any combination of two credible failures that will affect speed.

2.1.29
non-destructive evaluation
NDE
process or procedure for determining the quality or characteristics of a material, part or assembly without permanently altering the subject or its properties

NOTE In this International Standard, non-destructive evaluation is synonymous with non-destructive inspection (NDI) and non-destructive testing (NDT).

2.1.30
operating environments
all environments experienced during service life of the flywheel module

2.1.31
proof spin test
spin test run on a flight flywheel module at a pre-selected spinning speed that is higher than maximum expected operating speed

2.1.32
qualification tests
required formal tests used to demonstrate that the design, manufacturing and assembly have resulted in hardware conforming to specification requirements

NOTE Qualification test is synonymous with certification test.

2.1.33
service life
period of time (or cycles) starting with item inspection after the manufacturing and continuing through all testing, handling, storage, transportation, normal operation, refurbishment, re-testing and reuse that may be required or specified for that part

2.1.34
stress-rupture life
time during which the composite maintains structural integrity considering the combined effects of stress level(s), time at stress level(s) and associated environments

2.1.35
touchdown bearings
bearings required to act as the rotor suspension system in the non-operating mode and/or the backup suspension system in the operating mode during main suspension system failure

2.1.36
touchdown event
event that can occur with flywheel modules supported on magnetic bearings whereby the rotor is unexpectedly forced onto its touchdown bearings during normal operation due to malfunction of magnetic bearings, overload or other anomaly

2.1.37
ultimate load
product of the limit load and the design ultimate safety factor

NOTE The ultimate load is the load that the parts in a flywheel module need to withstand without catastrophic failure in the expected environment.

2.1.38
visual damage threshold
VDT
impact energy level shown by test(s) which creates an indication that is detectable by a trained inspector using an unaided visual technique

2.2 Symbols

a crack size

$\mathrm{d}a/\mathrm{d}N$ fatigue crack growth rate

I_p polar mass moment of inertia

I_t	transverse mass moment of inertia
K_{IC}	plane strain fracture toughness
K_{Iscc}	stress intensity threshold for stress-corrosion cracking
N	number of cycle
T_g	glass transition temperature

2.3 Abbreviated terms

ATP	Acceptance Test Programme
CT	Computer Tomography
FM	Flywheel Module
FMECA	Failure Mode, Effects and Criticality Analysis
FRA	Flywheel Rotor Assembly
KPP	Key Process Parameter
MDS	Maximum Design Speed
MEOS	Maximum Expected Operating Speed
MPE	Maximum Predicted Environment
MRB	Material Review Board
MS	Margin of Safety
NDE	Non-Destructive Evaluation
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
SP	Specification Performance
S-N	Stress versus Life
ε-N	Strain versus Life
VDT	Visual Damage Threshold

3 Requirements

3.1 General requirements

This clause presents the general requirements for the parts in the FM for

— design,

— material selection and characterization,

- fabrication and process control,
- quality assurance,
- repair and refurbishment, and
- storage.

Most of the requirements are specified for both manned and unmanned space systems.

NOTE Requirements primarily applicable to manned space systems are specifically stated and identified by an asterisk (*) which follows the clause/subclause title or which precedes the paragraph(s) concerned.

3.2 Design requirements

3.2.1 General design requirements

The general design requirements for the parts in the FM are delineated in 3.2.2 to 3.2.14.

3.2.2 System analysis

3.2.2.1 General

A thorough system analysis of the flywheel shall be used to establish design parameters for the FM.

3.2.2.2 System impact threat analysis*

For fracture critical non-metallic parts in the FM used in manned space systems, a system threat analysis shall be conducted to provide information for preparing the damage control plan. The threat analysis shall document the conditions (source and magnitude of threat) under which impact damage can occur.

3.2.2.3 Failure Mode, Effects and Criticality Analysis (FMECA)

A Failure Mode, Effects and Criticality Analysis (FMECA) shall be conducted. This analysis is used to systematically evaluate and document, by item failure mode analysis, the potential effect of each functional or hardware failure on mission success, personnel and system safety, system performance, maintainability and maintenance requirements. Each potential failure is ranked by the severity of its effect, in order that appropriate corrective actions may be taken to eliminate or control the high-risk items.

3.2.3 Loads, speeds and environments

The anticipated load, speed and associated temperatures throughout the service life of the flywheel shall be used to define the design load/temperature profile for the parts in the FM. Other environmental effects (radiation, corrosive atmosphere, vacuum, etc.) pertinent to the structural strength and life of these parts shall be considered, as appropriate.

Throughout this International Standard, limit load and maximum expected operating speed (MEOS) are used as the baseline load and speed.

NOTE The term maximum design speed (MDS) can be used for the design and testing of FMs. The basic difference between MDS and MEOS is the degree of consideration of potential credible failure within a FM, and the resultant effects on the speed of the FM during system operation. MDS is associated with manned systems and is based on the worst-case combination of two credible system failures. The criteria to be used for the determination of speed for a given design and application need to be clearly established by the contracting parties.

3.2.4 Strength

3.2.4.1 General

All parts in the FM shall possess adequate strength to preclude detrimental deformation at corresponding limit loads in the expected test and operating environments throughout their respective service lives. All parts in the FM shall also possess adequate strength to preclude catastrophic failure at design ultimate load.

3.2.4.2 Local yielding

Local yielding in an FM part due to secondary or peak stresses shall be acceptable only if all of the following are satisfied:

a) the structural integrity of the part shall be demonstrated by adequate analysis and/or test;

b) there shall be no detrimental deformation that affects FM function or stability; and

c) the service life requirements are met.

3.2.5 Static stiffness

All parts in the FM shall possess adequate stiffness to preclude detrimental deformation at corresponding limit loads in the expected test and operating environments throughout their respective service lives. All parts shall also possess adequate stiffness to preclude collapse at design ultimate load.

3.2.6 Rotor dynamics

This set of requirements shall be applied to FRAs in FMs. Natural frequencies and critical speeds shall not be of a type or of a frequency response that would be deleterious to the safety and operation of the flywheel system. Established and proven methods shall be followed to minimize the number of lateral critical speeds and natural frequencies within the operating range, and particularly those that are characterized by a higher level of strain energy within the rotor (e.g. bending modes of operation). Shaft-bending critical speeds in the operating speed range shall be avoided, if possible, but if they are present, it shall be demonstrated by test to be safe to operate at or through the critical speeds. Stability of the rotor to torsion, axial and lateral excitations (e.g. imbalance, motor torsion oscillations, seismic events, touchdown bearing impact) shall be maximized through the application of isolation, damping and/or related means to permit stable rotor performance.

3.2.7 Thermal

Thermal effects, including temperatures, thermal gradient, thermal stresses and deformations, and changes in the physical, mechanical, and the glass transition temperature (T_g) of the composite materials of construction, shall be considered in the design of all parts in the FM. These effects shall be based on temperature extremes in accordance with 3.2.3.

3.2.8 Static strength margin of safety

3.2.8.1 General

For all parts in the FM, the margin of safety (MS) shall be calculated by using material allowable strengths and the design safety factor. For metallic and composite parts, the minimum design ultimate safety factor shall be 1,5. To allow for local yielding in metallic parts, the yield design safety factor shall be 1,1. For bonded interfaces and ceramics parts, the minimum design ultimate safety factor shall be 2,0. All MSs shall be positive for all applicable loading conditions, such as launch, landing and touchdown event.

3.2.8.2 Manned space systems*

For manned space systems, MS calculations for fracture critical parts shall use A-basis allowables. Otherwise, B-basis allowables may be used. These allowables shall be derived from samples of size and shape representative of manufacturing to the greatest degree practical. Where properties are not attained from specimens tied closely to the FM geometry and manufacturing processes, a smaller number of specimens at the subcomponent level shall be tested to anchor these properties and account for size, shape and residual stress effects. The speed range used in this analysis shall encompass the MEOS, unless otherwise specified.

3.2.8.3 Unmanned space systems

For unmanned space systems, MS calculations may use B-basis allowables. These allowables shall also be derived from samples of size and shape representative of manufacturing to the greatest degree practical. Where properties are not attained from specimens tied closely to the FM geometry and manufacturing processes, a smaller number of specimens at the subcomponent level shall be tested to anchor these properties. The speed range used in this analysis shall encompass the MEOS, unless otherwise specified.

3.2.9 Fracture control*

3.2.9.1 Fracture critical selection criteria

Unless otherwise specified, rotating parts that meet containment requirements specified in 3.2.9.2 are not considered to be fracture critical.

Parts are fracture critical if it is credible that cracks in the part could lead to a catastrophic failure. For composite materials, the term crack also includes delamination, defects due to manufacturing, impact damage and in-service mechanical damage.

All fracture critical parts shall meet the damage-tolerance life requirements of 3.2.9.3. For composite fracture critical parts, the impact damage requirements of 3.2.9.4 shall also be satisfied.

3.2.9.2 Containment

For a rotating part to be classified as a contained part, it shall meet the following requirements:

a) it is clearly contained in associated housing/enclosure, etc.; and

b) it can be shown that the failure of the part will not cause a catastrophic hazard.

Analyses or tests shall be performed where there is uncertainty regarding containment of fragmented pieces.

3.2.9.3 Damage-tolerance life

In a manned space system, all fracture critical metallic and ceramic parts of the FM shall have adequate damage-tolerance life. It is required that the largest undetected crack applied that could exist in the fracture critical part shall not grow to failure when subjected to cyclic and sustained loads in a specified number of service lifetimes.

NOTE The largest undetected crack is consistent in size with the proof test limits or sensitivity of the non-destructive evaluation (NDE).

These loads shall be determined in accordance with the requirements in 3.2.3. Unless otherwise specified, the required damage tolerance life is service life multiplied by 4.

3.2.9.4 Impact damage tolerance

In a manned space system, the residual strength of a fracture critical composite part in the FM shall not be degraded below its ultimate load requirement after it has been subjected to the larger energy level of the system threat analysis impact or VDT impact.

A part having a static strength factor of safety of 4,0 or greater is not required to meet this impact damage tolerance requirement.

3.2.10 Fatigue life

All non-fracture critical parts in the FM in a manned space system, or all parts in the FM used in unmanned space systems, shall have adequate fatigue life in order to achieve mission success. Unless otherwise specified, fatigue life shall be service life multiplied by 4, with no induced damage or defects.

3.2.11 Time-dependent behaviour

All parts in the FM shall be designed to preclude excessive cumulative strain and/or stress redistribution as a function of time stemming from time-dependent material behaviour (e.g. creep, relaxation and thermal recovery), which would result in rupture, detrimental deformation/delamination or collapse (e.g. buckling) during its service life. Unless otherwise specified, time-dependent deformation analysis and/or testing shall account for durations of service life multiplied by 4.

3.2.12 Stress-rupture life

The composite parts in the FM shall be designed to meet the service life requirement, including the time that the FM is under sustained load. There shall be no credible composite fibre stress-rupture failure modes based on stress-rupture data for a specified probability of survival. The probability of survival shall be selected by the user for the intended application.

Unless otherwise specified, the minimum probability of survival associated with catastrophic failure shall be 0,999.

3.2.13 Corrosion and stress-corrosion control and prevention

Degradation of the parts in the FM due to the following factors shall be considered:

a) corrosive or incompatible environments;

b) galvanic corrosion resulting from the use of incompatible materials;

c) stress-corrosion cracking.

3.2.14 Outgassing

Contamination control analysis shall be used to evaluate performance impacts of outgassing on adjacent critical equipment. Venting ports shall be designed so that lubricant outgassing products do not directly impinge on critical surfaces.

Items that might produce deleterious outgassing while in orbit shall, where practical, be baked for a sufficient time to drive out all but an acceptable level of outgassing products before installation in the module. Where baking is not practical, exposure to vacuum within the operating temperature of the item shall be used.

3.3 Requirements for materials

3.3.1 Metallic materials

3.3.1.1 Metallic material selection

The selection of material for metallic parts of the FM shall be based on known material strengths and fatigue characteristics consistent with the overall system requirements.

*For manned space systems, fracture toughness and crack growth rates (da/dN) for all metallic fracture critical parts shall be considered. Use shall not be made of metallic materials which have a stress intensity threshold for stress-corrosion cracking (K_{Iscc}) of less than 60 % of the material's plane strain fracture toughness (K_{IC}) in the expected operating environment.

3.3.1.2 Metallic material evaluation

The selected metallic materials shall be evaluated with respect to

- material processing,
- fabrication methods,
- manufacturing operations,
- refurbishment procedures and processes, and
- other factors that affect the resulting strength and fracture properties of the material in both the fabricated and the refurbished configurations.

Materials that are susceptible to stress-corrosion cracking or embrittlement mechanisms such as hydrogen embrittlement shall be evaluated by performing sustained load fracture tests when applicable data are not available.

3.3.1.3 Metallic material characterization

The allowable mechanical properties and fracture properties of all metallic materials selected for metallic parts shall be characterized in sufficient detail to permit reliable and high confidence predictions of their structural performance in the expected operating environments, unless these properties are available from reliable sources.

Where material properties are not available, they shall be characterized by tests. Uniform test procedures shall be followed to determine material strength and fracture properties, as required. These procedures shall conform to recognized standards. The test specimens and procedures used shall provide valid test data for the intended application. Sufficient tests shall be conducted such that meaningful nominal values of fracture toughness, fatigue data and crack growth rate data corresponding to each alloy system, temper, product form, thermal and chemical environments and loading spectra can be established to evaluate compliance with strength, damage-tolerance life and/or fatigue requirements.

3.3.2 Composite materials

3.3.2.1 Composite material selection

Composite materials used for a part in the FM shall be selected on the basis of

- environmental compatibility,
- material strength/modulus,

- fatigue, and
- stress-rupture properties.

The effects of fabrication process, temperature/humidity, load spectra and other conditions such as aging, which may affect the strength and stiffness of the material in the fabricated configuration, shall also be included in the rationale for selecting the composite materials.

3.3.2.2 Composite material evaluation

The materials selected for a composite part in the FM shall be evaluated with respect to

- material processing,
- fabrication methods,
- manufacturing operations,
- processes, operating environments, service life, and
- other pertinent factors that affect the resulting strength and stiffness properties of the material in the fabricated configurations.

3.3.2.3 Composite material characterization

The properties of the composite materials selected shall be characterized in their expected operating environments. Test methods using samples representative of the manufacturing processes involved in FM hardware fabrication and accounting for residual stresses shall be followed to determine material properties as required. The test specimens and procedures used shall follow standardized test methods whenever available, in order to provide valid test data for the intended application.

The strength allowables of the composite material shall be determined from the testing of coupon, sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

3.3.3 Ceramic materials

3.3.3.1 Ceramic material selection

Material selection for ceramic parts of the FM shall be based on known material properties appropriate for the intended application. Key characteristics to be considered shall include

- fracture toughness,
- hardness,
- Weibull parameters,
- dimensional tolerances,
- environmental compatibility,
- elastic properties,
- thermal properties,
- electrical properties,

— surface finish, and

— surface quality (presence of surface defects caused by impurities).

For each type of ceramic component (bearing, magnet, etc.), the temperature and stress distributions shall be determined for both steady-state and transient operating conditions. These data shall then be used in conjunction with accepted life prediction programmes to make initial assessments of the probability of survival of the component over its intended lifetime. The minimum acceptable probability of survival will be set on the basis of mission requirements.

3.3.3.2 Ceramic material evaluation

The selected ceramic materials shall be evaluated with respect to

— material processing,

— manufacturing robustness,

— inspection protocols,

— refurbishment procedures and processes, and

— other factors that affect the functional performance of the material in both the fabricated and the refurbished configurations.

Materials that are susceptible to time- or cycle- (temperature or stress) dependent failure shall be evaluated by performing stress-rupture and/or cyclic fatigue tests when applicable data are not available.

3.3.3.3 Ceramic material characterization

The mechanical and thermal properties of all ceramic materials selected for FM parts shall be characterized in sufficient detail to permit reliable and high confidence predictions of the operating stresses and temperatures for steady-state and transient conditions. The Weibull and slow crack growth/cyclic fatigue parameters required for prediction of probability of survival shall be characterized as well. Potential sources of these data include the material suppliers, technical publications and established databases.

Where material properties are not available, they shall be characterized by established tests. When possible, these procedures shall conform to recognized standards. If no standards exist, the adopted test procedures shall be based on the best available methods as defined in the current technical literature. Sufficient tests shall be conducted so that statistically meaningful data corresponding to each material type, manufacturing method, product form and size, thermal and chemical environments and operating spectra can be established to evaluate compliance with strength, safe-life and/or fatigue requirements. Analyses shall be verified by conducting proof tests on ceramic components identical in material, geometry and manufacturing method to those used in the FM. The proof test conditions shall simulate the worst-case operating conditions appropriate for the component in question (e.g. rolling contact fatigue in the case of ceramic bearings and thermal transients for ceramic magnets).

3.3.4 Polymeric materials

3.3.4.1 Polymer material selection

Polymeric materials used for a part or for joining parts in the FM shall be selected on the basis of

— environmental compatibility,

— material strength/modulus,

— fatigue,

- creep deformation/relaxation,
- stress-rupture properties, and
- suitability as an adhesive, as dictated by the application.

The effects of fabrication process, temperature/humidity, load spectra and other conditions such as aging, which may affect the strength, stiffness and dimensional tolerance of the material in the fabricated configuration, shall also be included in the rationale for selecting the polymeric materials.

3.3.4.2 Polymer material evaluation

The materials selected for a polymeric part in the FM shall be evaluated with respect to

- material processing,
- manufacturing operations,
- processes, operating environments, service life, and
- other pertinent factors that affect the resulting strength, stiffness and dimensional tolerance properties of the material in the fabricated configurations.

3.3.4.3 Polymer material characterization

The properties of the polymeric materials selected shall be characterized in their expected configurations and operating environments. Test methods using samples representative of the manufacturing processes involved in FM hardware fabrication shall be used to determine material properties as required. The test specimens and procedures used shall follow standardized test methods whenever available, in order to provide valid test data for the intended application.

The strength allowables of the polymeric material shall be determined from the testing of coupon, sub-scale or full-scale composite parts. When sub-scale and coupon data are used in the database, correlation between coupon/sub-scale data and full-scale data shall be established.

3.4 Fabrication and process control

The design of the parts in the FM shall follow well-characterized fabrication processes and procedures. The fabrication process for parts in the FM shall be a controlled, documented process.

Proven processes and procedures for fabrication and repair of the metallic and ceramic parts in the FM shall be used to preclude damage or material degradation during material processing and manufacturing operations. In particular, special attention shall be given to ascertain that the thermal treatment, machining, drilling, grinding and other operations are within the state-of-the-art and are appropriate for the application.

*For manned space systems, the fracture toughness, mechanical and physical properties shall be within established design limits after exposure to the intended fabrication processes. Fracture control requirements and procedures shall be defined in applicable drawings and process specifications. Detailed fabrication instructions and controls shall exist to ensure proper implementation of the fracture control requirements.

Incorporated materials shall have certifications, which demonstrate acceptable variable ranges to ensure repeatable and reliable performance. The fabrication process shall control or eliminate detrimental conditions in the fabricated article.

An inspection plan shall be developed in accordance with 3.5.2, in order to identify all key process parameters (KPP) essential for verification. In-process inspection or process monitoring shall be used to verify the setup and the acceptability of critical parameters during the fabrication process.

3.5 Quality assurance

3.5.1 General

A quality assurance or inspection programme based on a comprehensive study of the product and engineering requirements shall be established to ensure that the necessary NDE and acceptance proof spin tests are performed effectively. The programme shall ensure that no damage or degradation has occurred during material processing, fabrication, inspection, acceptance tests, shipping, storage, assembly and operational use and refurbishment, and that defects which could cause failure are detected or evaluated and corrected. As a minimum, the points described in 3.5.2 to 3.5.5 shall be included in the quality assurance programme. Quality assurance data for all parts of the FM shall be maintained throughout the service life.

3.5.2 Inspection plan

An inspection master plan and sample plan shall be established prior to the start of fabrication. The plan shall specify appropriate inspection points and inspection techniques for use throughout the programme, beginning with material procurement and continuing through fabrication, assembly, acceptance proof spin test, shipment, assembly and operation, as appropriate. When establishing inspection points and inspection techniques, consideration shall be given to the material characteristics, fabrication processes, design concepts, corrosion control and accessibility for inspection of defects.

3.5.3 Inspection techniques

*For manned space systems, the inspection techniques selected for metallic parts shall have the capability to determine the size, geometry, location and orientation of a crack or a crack-like defect. Inspection techniques such as dye penetrant, magnetic particle, eddy current, radiography and ultrasound shall be used to detect cracks, as appropriate. Other NDE techniques used shall have a demonstrated 90 % probability of detection at a 95 % confidence level.

The inspection techniques for composite materials shall include visual inspection performed in conjunction with appropriate state-of-the-art NDE techniques. Inspections shall be performed to detect, as applicable

— non-uniform or broken fibres,

— delaminations,

— fibre wrinkles and waviness,

— dry fibres (i.e. fuzzing or “brooming”),

— machining damage,

— impact damage, and

— uniformity of surface coatings.

Inspections shall be augmented by use of optical magnification or solvent wipe techniques (i.e., for detection of cracks or delaminations). Proven NDE techniques, such as ultrasound, radiography, thermography, computer tomography (CT) and shearography, shall be used to identify and characterize critical defects, as appropriate. The appropriateness and capability of the NDE methods selected to detect and characterize critical defects shall be established.

3.5.4 Inspection data

Inspection data for the parts in the FM shall be maintained throughout the service life. These data shall be reviewed periodically and assessed to evaluate trends and anomalies associated with the inspection procedures, equipment and personnel, material characteristics, fabrication processes, design concept and structural configuration. The result of this assessment shall form the basis of any required corrective action.

3.5.5 Traceability*

For manned space systems, traceability shall be maintained on all fracture critical parts in the FM throughout their development, manufacturing, testing and service. Serialization shall be required on each fracture critical component and they shall have traceability to material heat treat or composite manufacture/cure lot as a minimum. A log shall be maintained for each part of the FM to record all significant manufacturing assembly processes, load/spin cycles, inspections and tests occurring during the time period from fabrication to the end of service life. Engineering drawings for fracture critical parts shall contain notes which label the part “fracture critical” and which specify the appropriate inspections or flaw screening method to be used.

3.6 Repair and refurbishment

When inspections reveal structural damage or defects exceeding the permissible levels, the non-conforming part shall be assessed by a material review board (MRB) for repair, refurbishment or replacement. All repairs and refurbishments shall follow an approved repair process. All repaired or refurbished hardware shall be verified after each repair and refurbishment by the applicable analysis and/or acceptance test procedure for new hardware to demonstrate their structural integrity and to establish their suitability for continued service.

3.7 Storage requirements

When parts of the FM are put into storage, they shall be protected against

— exposure to adverse environments (e.g. temperature, humidity), and

— in-service damage (e.g. abrasion, cutting, impact).

Critical environmental conditions shall be recorded.

3.8 Transportation requirements

When the FM parts or subassemblies or the whole module are transported, they shall be packaged in a manner that will provide protection against damage from physical or environmental sources. These include, but are not limited to,

a) exposure to adverse environmental conditions (e.g. temperature extremes, humidity, water, prolonged exposure to sunlight),

b) physical impact,

c) vibration, and

d) shock during transport.

Critical environmental and transportation conditions that pose a threat to the integrity of the FM, such as temperature extremes, excessive vibration or maximum shock loading, shall be recorded. The nature of recording (i.e. continuous versus maximums) and parameters to be monitored shall be commensurate with the threat assessment for the method of transportation and the consequences of these transportation parameters on the FM. As a minimum, records shall be kept which document

— transportation events,

— packaging used,

— method of conveyance,

— person or company responsible for transport,

— dates of shipment and receipt, and

— a written record (possibly including photographs) of the results of a visual inspection of the package and its contents for damage or movement during the transportation process.

Any adverse events or observations shall be recorded and assessed for implications on the safety of the FM.

4 Verification requirements

4.1 Design requirements verification

4.1.1 General

Design requirements verification, as outlined in this clause, is carried out by means of analysis, test and document review. The purpose of the verification process is to ascertain that

a) the design meets the specified requirements and is acceptable for the intended use, and

b) parts manufactured to the qualified design meet specified requirements for materials, manufacturing processes and workmanship.

4.1.2 System analysis verification

4.1.2.1 General

The system analysis report shall be reviewed for its adequacy.

4.1.2.2 System impact threat analysis verification

The system impact threat analysis report, which documents the source and magnitude of the impact damage threat, shall be reviewed.

4.1.2.3 FMECA verification

The report that documents the results of the FMECA of a FM shall be reviewed periodically in order to ensure that the analyses were performed and are adequate.

4.1.3 Loads, speeds and environments verification

The anticipated loads and associated temperature and other environments shall be documented and reviewed for adequacy.

4.1.4 Strength verification

Test results of the acceptance proof spin test specified in 4.3.3 and the ultimate load test specified in 4.2.11 shall be used to verify the strength requirements.

4.1.5 Static stiffness verification

Stress analysis results shall be used for analytical verification of static stiffness requirements. Test results of the acceptance proof spin test specified in 4.3.3 and ultimate load test specified in 4.2.11 shall be used to verify the stiffness requirements.

4.1.6 Rotor dynamics verification

4.1.6.1 Rotor dynamics requirements, as specified in 3.2.6, shall be verified through analysis and/or testing. The following are specific verification requirements:

a) verify through analysis that the ratio of the rotor assembly's polar mass moment of inertia to the transverse mass moment of inertia (I_p/I_t) is outside the range of 0,8 to 1,2, unless it is verified through testing that the rotor can run stably at all intended speeds inside this range;

b) verify through testing the zero speed free-free rotor modes on the rotor assembly via suspended rap tests to check accuracy of analysis model(s).

4.1.6.2 For FRA suspended on magnetic bearings, the following verification requirements shall be met:

a) verify through analysis that the rotor assembly's first forward whirl shaft-bending critical speed is above MEOS multiplied by 1,25 on frequency assuming the free-free support case, unless it is verified through testing that the rotor can run stably near a shaft-bending resonance or through such a resonance;

b) verify through analysis that the rotor remains stable under MEOS multiplied by 1,25, i.e. at shaft-bending critical speed when on backup bearings in touchdown events using appropriate bearing stiffness values, unless it is verified through testing that the rotor can operate stably near or through such a resonance on backup bearings in a touchdown event.

4.1.6.3 For rotor assemblies suspended on mechanical bearings during normal operations, the following verification requirements shall be met:

a) verify through analysis that the rotor assembly's first shaft-bending critical speed is MEOS multiplied by 1,20 if dampers which significantly suppress shaft-bending mode vibration are incorporated;

b) verify through analysis that the rotor assembly's first shaft-bending critical speed is MEOS multiplied by 1,15 if no dampers are used, unless it is verified through testing that the rotor can run stably with less margin from a shaft-bending resonance or through such a resonance.

4.1.6.4 Rotor dynamics analyses shall be performed using appropriate rotor dynamics code or finite element code that accounts for cross coupling and gyroscopic effects.

4.1.7 Thermal verification

Thermal requirements shall be verified through thermal analysis and thermal test, as specified in 4.3.4.

4.1.8 Static strength MS verification

MS calculations shall be verified by stress analyses supported by testing or through run-to-failure testing. The stress analysis of each part in the FM shall be conducted with the assumption that no defects exist in the parts. The analysis shall determine stresses for all load cases in service life, especially the combined effects of rotation and flight induced loads. Finite element or other structural analysis techniques shall be used to perform the required stress analysis. For composites, effects of parameters (e.g. winding angles, winding sequences) shall be assessed. Analysis tools shall be correlated against test results in order to demonstrate the accuracy of the methodology, and independently verified with industry accepted tools, where practical. The analytical tool verification shall be submitted as part of the stress analysis report, when required.

4.1.9 Fracture control verification*

4.1.9.1 General

Fracture control requirements shall be verified through analysis and/or test. If a part can be shown by analysis or testing to be contained or surrounded by other subjects when failure occurs, it is not fracture critical. If it can be shown to be fail-safe or to possess low release energy, it is not fracture critical. The final fracture critical parts list shall be reviewed to ensure that the selection criteria are met.

4.1.9.2 Containment verification

Containment housing that is part of the FM shall be verified by documented engineering practice where it is clear that containment exists, or it shall be shown by analysis using proven analytical methodology or by testing where there is uncertainty concerning the analysis. It shall be verified that not only the parts are contained, but that the energy released and resulting reaction loads and torques on the containment system do not create a catastrophic hazard in the supporting structure of a space system or in the ground test facility during development, qualification or acceptance tests.

4.1.9.3 Damage-tolerance life verification*

A damage-tolerance life verification shall be conducted on fracture critical metallic and ceramic parts in a FM used in a manned space system. Damage-tolerance safe analysis (also referred to as fracture mechanics crack-growth analysis) shall be performed to verify that it meets the damage-tolerance life requirements specified in 3.2.9. Undetected crack(s) shall be assumed to be in the critical location(s) and in the most unfavourable orientation(s) with respect to the applied stress and material properties. The size of the crack(s) shall be based on the appropriate NDE technique(s) used in the acceptance tests. Nominal values of fracture toughness and crack growth rate (da/dN) data shall be used in the analysis. If a proof spin test is used to define the limits on initial crack size for damage-tolerance life determination, it shall be demonstrated by analysis or test that the proof spin test will ensure the required life is obtained, including effects of

— stable crack growth during proof spin test,

— anomalous behaviour of cracks approaching surface boundaries or in welds, and

— test environments.

Damage-tolerance life verification for fracture critical metallic and ceramic parts can be performed by testing using a flight-like part, with controlled size of crack(s). Coupons shall be allowed only for metallic parts when the stress field is well defined and the material properties are representative to that of the flight parts. The size and shape of crack(s) shall correspond to the detection capability of the NDE to be imposed on the flight part.

Damage-tolerance life verification for fracture critical composite parts in the FM used in manned space system shall be performed by testing only. Test spectrum shall include all cycles, time and environments associated with part service life. Accelerated test techniques can be used when proven. Damage-tolerance test(s) for fracture critical composite parts shall be performed by using full-scale, flight-like articles, with pre-fabricated crack(s). The term “crack” also covers delamination and other mechanical damage induced in service, including surface cuts and abrasions apart from impact damage. Impact damage shall meet the requirements specified in 4.1.9.4. The shape and size of the controlled cracks shall be greater than or equal to the detection capability of the NDE imposed on the flight parts.

4.1.9.4 Impact damage-tolerance verification*

Testing is the only acceptable method for fracture critical composite parts in the FM for demonstrating impact damage-tolerance. Impact damage-tolerance is verified when residual strength is shown not to degrade below the design ultimate load. Full-scale articles that are representative of the flight part, with induced impact damage, shall be used as the test specimens. Either system threat analysis energy levels or verified VDT energy levels, whichever is greater, shall be used in the determination of impact energy level in the impact damage-tolerance tests.

4.1.10 Fatigue life verification

4.1.10.1 General

Fatigue life shall be verified for non-fracture critical FM parts by fatigue analysis or testing using the load/temperature profile defined in accordance with 3.2.3. Fracture mechanics based damage-tolerance analysis/testing may be used as a substitute for fatigue analysis/testing if mission success requirements warrant it. Unless otherwise specified, fatigue life and damage-tolerance life shall be service life multiplied by 4.

4.1.10.2 Fatigue analysis

When a fatigue analysis is used to verify the fatigue life of a part in the FM, nominal values of fatigue characteristics, including stress versus life (S-N) data and/or strain versus life (ε-N) data of the material shall be used. These data shall be taken from reliable sources. The analysis shall account for the spectra of expected operating loads and environments. Miner's Rule is an acceptable method for handling variable amplitude fatigue cyclic loading. The limit for accumulated damage shall be 80 % of the normal limit.

4.1.10.3 Fatigue testing

Testing of unflawed specimens to demonstrate fatigue life of a specific part, together with stress analysis, is an acceptable alternative to analytical prediction.

When approved by the procuring agency, the fatigue life test does not need to be completed before the scheduled launch.

4.1.11 Time-dependent behaviour verification

Time-dependent deformation of all parts in the FM shall be verified through analysis and/or testing using the load/temperature profile defined in accordance with 3.2.3. If such deformation is related to initiation or propagation of crack-like defects in fracture critical parts, damage-tolerance (safe-life) verification takes precedence.

If the time-dependent deformation is related to initiation or propagation of crack-like defects in fracture critical composite parts, verification shall be demonstrated by testing of worst-case crack-like defects in the most unfavourable locations in which they can be expected to occur. The orientation of crack-like defects shall also be representative of the worst-case condition that can be expected to occur.

4.1.12 Stress-rupture life verification

Stress-rupture life for composite parts in the FM shall be verified by analysis supported by test data using load/temperature profile defined in accordance with 3.2.3.

4.1.13 Corrosion and stress-corrosion control and prevention verification

A corrosion control plan for FM parts that are prone to stress-corrosion cracking or corrosion due to environmental or galvanic effects shall be reviewed for its adequacy.

4.1.14 Outgassing verification

Outgassing levels of FM materials for the specified operating conditions shall be shown by analysis, testing or documented engineering practice to be less than the allowable specified. The effects of outgassing on material properties, dimensional characteristics and residual stresses within the FM shall be established and included in the determination of material properties, analytical evaluations and/or experimental validations.

4.2 Qualification tests

4.2.1 General

Qualification tests shall be conducted either at the part level, the FRA level or the module level. In general, the tests shall be conducted on a single article. Test article configuration and test attachment shall be representative to flight configuration. However, life tests may be conducted on separate articles. Any ground testing of the FM requires proper and conservative containment and shielding. Safety precautions shall be reviewed thoroughly with the responsible authority. As a minimum, the qualification test programme shall consist of the following tests, and the test sequence shall be defined for each project:

a) spin test;

b) specification performance test;

c) thermal vacuum test;

d) vibration and shock tests;

e) electromagnetic compatibility (EMC) test;

f) modal survey test;

g) fault tolerance test(s);

h) life test;

i) ultimate load test.

4.2.2 Inspection

Inspections shall be performed after each major test to ensure that all hardware conforms to applicable drawings and specifications for functional performance. Criteria for determining acceptance or rejection of items shall be established.

4.2.3 Spin test

Each qualification test article shall be subjected to a spin test, as specified in 4.3.3.

4.2.4 Specification performance (SP) test

An SP test (also referred to as “functional test”) demonstrates that the mechanical and electrical performance of the FM meets the specification requirements plus the desired qualification margin after exposure to one or more of the environmental conditions predicted during the mission. An SP test may also verify mechanical or electrical ground support equipment compatibility and operation, as well as software algorithms used to command or monitor the performance of the FM. Although a comprehensive performance test is required to verify all specification requirements, it may not be necessary to verify all requirements at each step of the qualification process. Accordingly, it is possible and expected that the complete performance test be performed at the start, end and after critical environmental conditions, but a subset may be sufficient for verifying compliance after specific environmental conditions.

An SP test shall be developed and implemented to evaluate the performance of the FM after each major environmental test to ensure that the performance of the FM has not been affected by the test. The SP test may be different for each environmental test to ensure that those performances expected to be affected are verified, e.g. the SP test could include a cycle to maximum normal operating speed corresponding to one charge-discharge cycle.

An SP test may be performed after the vibration and thermal vacuum tests to assess the impact of each environmental test, although performance tests may be different after each environmental test type. It is also acceptable to complete performance tests only after completion of environmental tests, but there is more risk inherent in this approach.

Essential environmental conditions corresponding to checked operation mode shall be simulated in the SP test. Functional checks in the presence of environments can be conducted in other environmental tests.

4.2.5 Thermal vacuum test

A thermal vacuum test shall be conducted to demonstrate the ability of the FM to perform in the qualification thermal vacuum environment and to endure the thermal vacuum testing imposed on flight FMs during acceptance testing. It also serves to verify the FM thermal design.

Unless otherwise specified, the qualification test levels and duration are as follows:

a) pressure: $\leqslant 1{,}333\,224 \times 10^{-2}$ Pa[1)] for hardware subjected to space vacuum conditions;

NOTE For hardware that is to be enclosed in a hermetically sealed enclosure during service, the vacuum requirement needs to replicate the design vacuum.

b) temperature: 10 °C beyond acceptance temperature, or –34 °C to +71 °C (minimum range);

c) curation: 6 cycles.

The FM shall remain operational except during the first and last cycle, where the FM turn-off and turn-on shall occur. After the thermal vacuum environmental test, the FM shall be inspected. An SP test shall be conducted before and after the thermal vacuum test to verify that the FM is capable of withstanding the qualification level of this test.

4.2.6 Vibration and shock tests

4.2.6.1 General

The FM shall undergo appropriate vibration and shock test(s).

4.2.6.2 Vibration test

A vibration test shall be conducted to demonstrate the ability of the FM to endure the vibration environment of service including, as a minimum, the acceptance test and the transportation, launch and in-orbit phases of the mission with the desired qualification margin. Two types of vibration test shall be conducted as appropriate:

— sine vibration test, and

— random vibration test.

It is acceptable to conduct one type of these tests if peak response at each frequency and cumulative damage can be enveloped by both tests.

Unless otherwise specified, the qualification vibration test levels and duration are as described below.

a) **Sine vibration test level** Two octaves/min unless the sweep rates and dwell time can be based on the persistence of the environment in service use. The vibration levels shall be sufficient to cover the severity of the maximum design levels, which shall be at least 1,4 times higher than maximum predicted environment but shall not induce unphysical response.

b) **Random vibration test level** 3 dB above maximum predicted environment for 2 min in each of three orthogonal axes.

Test frequency range shall be defined by the users. An SP test shall be conducted before and after vibration tests to verify that the FM is capable of withstanding qualification level vibration tests.

1) 1 Torr = 133,322 4 Pa.