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Space systems — Vibration testing

Systèmes spatiaux — Essais de vibration

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Foreword

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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).

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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 vehicle*, 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

Vibration testing is one of the most important test items of space systems. The primary goals of vibration testing are to verify the design and to detect manufacturing issues of spacecraft, subsystems and units that could result in in-flight failures. In design, material selection, manufacture, assembly and integration phase, the test aims on exposing defects and non-conformances existing and eliminating potential quality problems. With regard to the launch phase, it also serves to prevent structural failure of a space system, loosening of fasteners and connectors, failure of electronic components, leakage of sealing elements or malfunction of mechanical system.

During vibration testing, over-testing can result in unnecessary destruction of the test specimen. In the 1990s, at the Jet Propulsion Laboratory, Mr. Terry Scharton elaborated the methodology of force notching for qualification of satellites and spacecraft to mitigate unnecessary over-testing. Since then, several attempts have been made to establish this methodology for a broader range of application. This document includes the methodology of force-based testing.

Space systems — Vibration testing

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document provides guidance and requirements for test providers and interested parties to implement vibration testing.

This document specifies methods, including the force limiting approach, to mitigate unnecessary over-testing of spacecraft, subsystems and units for space application.

The technical requirements in this document can be tailored to meet the actual test objectives.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitute 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 15864:2021, *Space systems — General test methods for space craft, subsystems and units*

ISO 19924:2017, *Space systems — Acoustic testing*

3 Terms and definitions

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

ISO and IEC maintain terminological 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
notching
reduction of the input level or spectrum in a vibration testing to limit structural responses at resonant frequencies according to qualification or acceptance loads to avoid over-testing.

3.2
response limited vibration testing
reduction of input acceleration in a vibration testing to maintain the measured response at or below a specified value

3.3
force limited vibration testing
reduction of reaction force in a vibration testing to specified values, which are usually the interface forces predicted for flight, plus a desired margin.

3.4
statistical DOF
number of independent variables in a statistical estimate of a probability

Note 1 to entry: The number of degrees of freedom determines the statistical accuracy of an estimate.

[SOURCE: ISO 2041:2018, 3.5.16, modified — The term has been changed from "statistical degrees of freedom" to "statistical DOF".]

4 Abbreviated terms

For the purposes of this document, the abbreviated terms described in Table 1 apply.

Table 1 — Abbreviated terms

DOF	degree of freedom
FEA	finite element analysis
FLV	force limited vibration
FLVT	force limited vibration test
FMD	force measurement device
FRF	frequency response function
POGO	propulsion generated oscillations
PSD	power spectral density
RMS	root mean square
TDFS	two-degree of freedom system

5 General

Vibration testing is distinguished between sinusoidal vibration testing and random vibration testing.

Sinusoidal vibration testing is intended to simulate the vibration environment produce by unstable combustion, by coupling of structural resonant frequencies (POGO), by imbalances in rotating equipment. Sinusoidal vibration testing is also to simulate ground transportation and handling, due to resonant responses of tires and suspension systems of the transporters.

Random vibrations are generated by the launcher engines and by acoustic and aerodynamic excitation of the launch vehicle and spacecraft fairing. During flight or ground transportation and handling, broad band vibration environment is imposed on the spacecraft. ISO 15864 recommends either vibration or acoustic testing, whichever is more appropriate, with the other one left optional. Generally, if acoustic testing is performed, random vibration may be skipped. For a small compact spacecraft, acoustic testing does not provide adequate environmental simulation, and random vibration may replace the acoustic test. To take this decision it is important to consider:

— vibration testing do not reach high frequency contents;

— whether the structure is sensitive to acoustic loads;

— whether the structure is sensitive to acoustic loads where the units are mounted.

Information for random vibration and acoustic test tailoring is provided in Annex A.

Conventional acceleration control during vibration testing may lead to the so-called over-testing problem due to the difference of the interface impedance of the mounting structure and the shaker. In order to overcome this problem, the force limited vibration (FLV) testing technique was developed. In the FLV testing, in addition to the acceleration specification, the specification of the reaction force between fixture and test specimen shall be defined. Using the FLV technique, both the acceleration and force at the interface of test specimen and fixture are limited so that the vibration environment characterizes the real situation more precisely.

6 Test technical requirements

6.1 Test specification

The test specification shall meet the requirements of the respective launch vehicle user manual.

The test specification generally includes testing level, frequency range, test direction and test duration. The duration of sinusoidal vibration testing is determined by the sweep rate and frequency range. The duration of random vibration testing is expressed in seconds or minutes. The test directions usually correspond with the three orthogonal axes, one of which is in accordance with the launch direction.

If FLVT will be applied, the test specifications shall be extended with the FLVT requirements.

When needed to re-check workmanship by dynamic mechanical environmental test for flight units that have undergone rework and that required random vibration testing at acceptance test, the minimum retesting shall be random vibration testing at workmanship screening level to be agreed with the customer. However, if the most effective single axis of workmanship screening re-test for all the reworked areas is determined, re-test excitation can be based just on that axis.

6.2 Tolerances

The tolerances shall be determined based on the design standard. If not specified otherwise, the following test level tolerances can be used.

a) Sinusoidal vibration

Frequency: −2 % to +2 % (or −1 Hz to +1 Hz, whichever is greater)

Acceleration amplitude: −10 % to +10 %

b) Random vibration

Acceleration spectral density (frequency resolution better than 10 Hz)

10 Hz to 100 Hz (analysis bandwidth 10 Hz or narrower): −3 dB to +3 dB

100 Hz to 1 000 Hz (analysis bandwidth is 10 % or narrower of the central frequency): −3 dB to +3 dB

1 000 Hz to 2 000 Hz (analysis bandwidth 100 Hz or narrower): −3 dB to +3 dB

Statistical DOF: not less than 100

Overall grms.: −10 % to +10 %

Test duration: −0 % to +10 %

6.3 Test control

6.3.1 Control strategy

6.3.1.1 General

The control strategy shall provide the required vibration at the required locations in or on the test specimen. This depends on the kind of vibration to be generated and on the test specimen/shaker interaction. Generally, a single strategy is appropriate (e.g. only acceleration input control strategy is used). There are cases where multiple strategies are used simultaneously (e.g. acceleration input control strategy and force limited vibration testing strategy are used simultaneously).

6.3.1.2 Acceleration input control

Acceleration input control is the basic method of vibration testing. The control accelerometers shall be mounted on the fixture at the test specimen mounting points. Shaker motion shall be controlled with feedback from the control accelerometer(s) to provide defined vibration levels at the fixture/ test specimen interface.

6.3.1.3 Notching

Notching is a general accepted practice in full-level vibration testing to avoid over-testing. Implementation of notching shall be subject to customer approval and relevant to Launcher authority approval. Refer to Annex B for an example of the notching calculate method. The following requirements apply.

a) The force on the main structure shall not be higher than the design value of quasi-static load plus a desired margin.

b) The vibration level shall not be less than the level of coupling analysis result for the interface between spacecraft and launcher, unless agreed by the launcher authority.

c) The response of key equipment fixed position shall not be higher than the equipment vibration testing level.

6.3.1.4 Force limited vibration testing

For force limited vibration testing, the vibration level is defined by acceleration. In addition, the reaction force between fixture and test specimen shall be measured and limited. Dynamic force gauges are mounted between the fixture and the test specimen. If the force achieves the limited value, the exciter motion shall be controlled with feedback from the force gages.

Force limiting is most useful for test specimens that exhibit distinct, lightly damped resonances on the shaker. The amount of relief available from force limiting is greatest when the structural impedance of the test specimen is equal to, or greater than that of the mounting structure in the actual mounting situation.

The force limit value shall be slightly larger than the real reaction force of the interface during launch, plus the desired margin. Force limits value can be determined in several ways including simple and complex TDFS Method, semi-empirical method, FEA method, quasi-static-load method, apparent masses envelope method and design/flight loads method. A non-exhaustive list of force limit method is specified in Annex C.

6.3.1.5 Response limited vibration testing

For response limited vibration testing, the vibration level is defined by acceleration. In addition, vibration response limits at specific points on the test specimen shall be defined. Monitoring accelerometers shall be located at these points. The test specimen shall be excited using control point accelerometer signals to control the exciters. The control inputs shall be automatically modified as needed to limit responses at the monitoring accelerometers to the predefined limits. This strategy is used to avoid damage to the specific equipment or lower level assembly.

6.3.2 Control point

The control accelerometer(s) shall be mounted on the test fixture near the specimen attachment points. For multiple-point control, an even distribution should be adopted. In case specific requirements exist, the positions of the control points shall be determined accordingly. If more than one control accelerometer is used, the test levels may be controlled by a control scheme either based on the average response or on the response extremes. The control scheme shall be consistent with the test requirement.

6.4 Specimen configuration requirements

The specimen configuration shall be as described in ISO 15864:2021, 7.13.3 and 7.14.3.

6.5 Response measurement point

The test requirements shall specify the number, installation position and orientation, type and measurement range of test sensors, as well as the processing modes and requirements for data measurement. See more detailed requirements in 7.2.5.

6.6 Test success criteria

It is presupposed that an accomplished test is formally compliant with the contract requirements.

For the test provider, if not specified otherwise, the following requirements shall apply.

— All vibration testing shall be applied at the right test level.

— The acquisition of test specimen vibration response data shall be complete and valid.

For the specimen provider, if not specified otherwise, the following requirements shall apply.

— The intended test purposes shall be achieved.

— There shall be no visual damage to the test specimen.

— The characteristic response curve (which includes the resonance frequencies and the amplification ratio) shall be the same before and after each full level vibration testing (see 8.2.3 a)) under consideration of the specified tolerance bands.

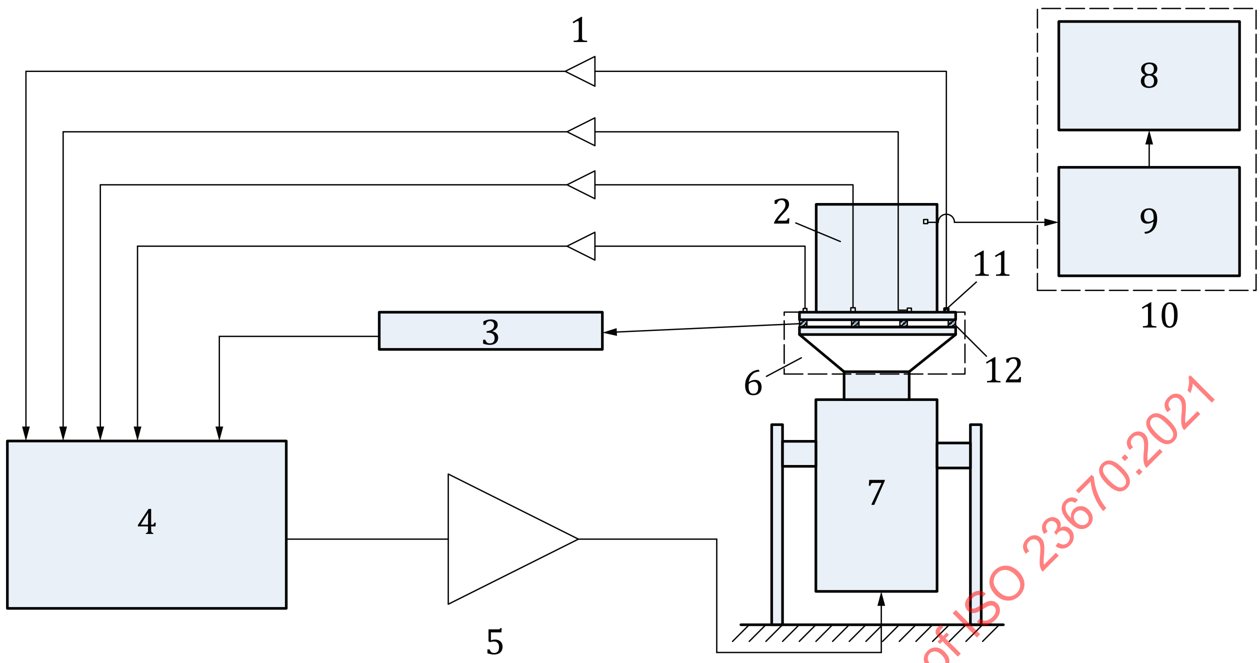
— The test specimen performance after the test shall be specified by the customer.

7 Test system

7.1 Test facility requirements

A vibration testing facility includes a vibration excitation system, a vibration control system, a measuring system and auxiliary equipment. An example of a vibration testing facility is shown in Figure 1.

For FLVT, dynamic force gauges are mounted between the shaker/fixture and the test specimen. The force at the interface is measured by the force gauges and is fed back to the control system to implement response limiting.



Key

1 accelerance signal conditioner
2 test specimen
3 force signal conditioner
4 vibration controller
5 power amplifier
6 force measurement device (for FLV)
7 shaker
8 data storage and processing system
9 data acquisition system
10 measurement system
11 accelerometer
12 force gauge

Figure 1 — Illustration of a force limited testing system

The test facility, including all auxiliary equipment,

— shall provide the specified vibration environments,

— shall implement the required control strategies, and

— shall meet the specified tolerances.

Measurement transducers, data recording and data reduction equipment capable of measuring, recording, analysing, and displaying data shall be sufficient to document the test and to acquire any additional data required.

The facility shall be maintained in regular intervals and shall be checked before test campaign.

7.2 Equipment requirements

7.2.1 Shaker

The requirements of the shaker are as follows.

a) The shaker test facility shall fulfil the requirements of the test concerning power, dimension, applicable forces and moments with a margin. The test requirements shall not be limited by the shaker performance.

b) The static load capacity shall be greater than the sum of mass of the test specimen, moving part of the shaker and the fixture. Flexible supports are necessary if this requirement cannot be met. The natural frequency of this supporting system shall be less than the lowest test frequency, and the allowed displacement shall be no less than the required displacement.

c) The maximum displacement of shaker shall be greater than that required by the test conditions.

d) The shaker frequency range shall allow reaching the upper and lower limit frequencies specified in the test conditions.

7.2.2 Fixture

The requirements for the test fixture are as follows.

a) The fixture stiffness-and-mass ratio shall be as large as possible.

b) The fixture shall mate with the test specimen in the same way as the flight interface does, so that the interface load distribution is similar to that in flight.

c) The acceleration response of the interface between fixture and test specimen shall be uniform in the test frequency range.

d) The first natural frequency of the fixture shall be higher than the higher frequency of the vibration testing. When this requirement cannot be met, the first natural frequency of the fixture is a number of times “*N*” of the first natural frequency of the test specimen. The number of times “*N*” shall be greater than 3 and agreed with the customer. Any additional notching or input level reduction cause by the fixture shall comply with requirements of 6.3.

e) S force measurement device is used as test fixture in FLVT, requirements for a force measurement device are specified in 7.2.3.

f) The vibration fixture configuration, and its interfaces to the test specimen / vibration source / other ground support equipment, shall be defined, inspected, fit checked and proof tested well before the vibration testing is carried out.

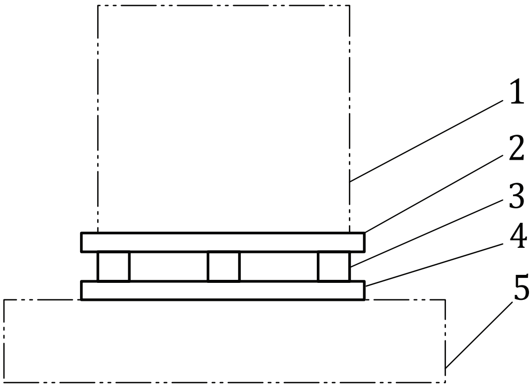
7.2.3 Force measurement device (FMD)

7.2.3.1 General

In case a force limited vibration testing is performed, a force measurement device (FMD) shall be utilized instead of the fixture specified in 7.2.2 for both the support of the test specimen and the measurement of the force at the interface between the test specimen and the shaker.

7.2.3.2 Force measurement device design

A force measurement device consists of three parts: an upper-adapter, tri-axial force gauges and a lower-adapter. A sketch of a typical FMD is illustrated in Figure 2.



Key

1 test specimen

2 upper-adapter

3 tri-axial force gauges

4 lower-adapter

5 shaker

Figure 2 — An illustration of a typical FMD

The mass of the upper-adapter should be as small as possible, normally less than 10 % of the test specimen. The resonance frequency of an FMD shall be no less than the upper limit of the test frequency.

For tri-axial force gauges, the following requirements and recommendations apply.

a) Piezo-electric force gauges should be used. The dimensions and dynamics shall be chosen according to the structure of the test specimen and the test level.

b) Multiple force gauges should be normally evenly distributed to obtain a better test result.

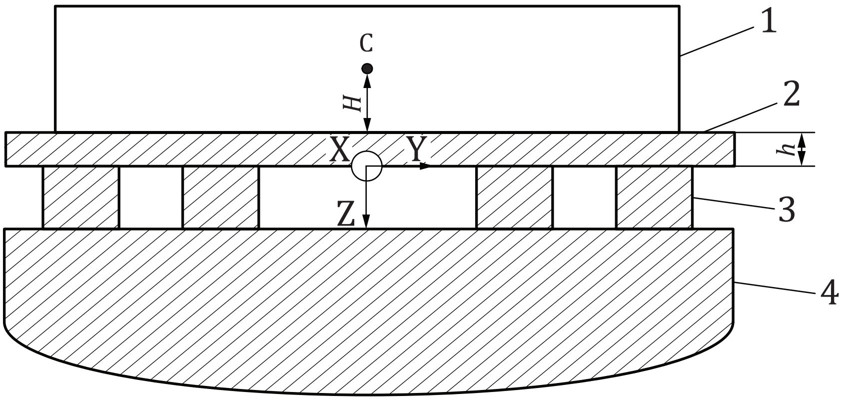
c) The force gauges shall be pre-loaded (normally by the manufacturer) before used in force limited vibration testing.

d) The influence of dynamic behaviour caused by FMD shall be assessed to comply with requirements of 6.3.

7.2.3.3 Force measurement device verification

7.2.3.3.1 General

Multiple tri-axial force gauges are often used to implement force limited vibration testing. A typical force measurement device is illustrated in Figure 3. The resultant force and resultant moment depend on the distribution of force gauges. A typical FMD is described and corresponding resultant force and resultant moments are formulated in Annex C.



Key

1 test specimen

2 upper-adapter

C centre of gravity of the test specimen

h height of the upper-adapter

3 tri-axial force gauges

4 lower-adapter

X, Y, Z directions of the reference system of the test item

H distance from the centre of gravity of the test specimen to the top of the upper-adapter

Figure 3 — Illustration of a typical force measurement device

7.2.3.3.2 FMD verification of vertical direction

Without loss of generality, assume that a test specimen vibrates along the Z axis during a test in the vertical direction. The forces measured by each force gauge in each direction as well as the resultant force and resultant moment shall be verified by a rigid body mass properties of the test item including upper adapter. The verification test frequency shall be lower than the first resonant frequency so that the dynamic amplification is negligible. Normally the beginning frequency of the test is picked for the verification.

Ideally, the verification criterion is that all the resultant forces and moments shall be equal to zero except in the Z direction. The measured forces in the Z direction for all force gauges should be equal to or rather similar to each other.

7.2.3.3.3 FMD verification of horizontal direction

Without loss of generality, assume that a test specimen vibrates along the Y axis during a test in the horizontal direction. The verification test frequency shall be lower than the first resonant frequency so that the dynamic amplification is negligible. Normally the beginning frequency of the test is picked for the verification.

The verification criterion of the horizontal direction is as follows: Ideally, all the resultant forces and moments shall be equal to zero except the resultant force in the Y direction and the bending moment in the X direction. The transverse forces for all force gauges should be similar to each other. The phase is the same for the Z direction forces for the transducers with –Y coordinate and are opposite of those transducers with +Y coordinate.

7.2.4 Vibration control system

A vibration control system typically includes: vibration controller, acceleration sensor, signal conditioning system. The acceleration sensor and the signal conditioner shall meet the relevant requirements of 7.2.5.2 and 7.2.5.4. The vibration control system shall meet the following requirements.

a) The vibration control system shall at least have the functions of sinusoidal vibration and random vibration testing control.

b) The vibration controller shall have the functions of multi-point averaging, maximum or minimum control.

c) The vibration controller shall have a response limit function.

d) For force limit vibration testing, dual controlled vibration testing shall be used. This means controlling the test by acceleration control channels and additional notching channels for the defined force limits.

   1) The vibration controller shall be capable of “extremal control,” (also called maximum or peak control). In extremal control, the largest of a set of signals is limited to a single reference spectrum.

   2) The vibration controller shall accommodate different reference spectra for limiting individual response (and force) measurement channels.

e) The vibration controller shall have an automatic abort function to avoid overloads on a test specimen due to control disturbance.

7.2.5 Measurement system

7.2.5.1 General

Typically, the measurement system is composed of sensors (e.g. accelerometer, strain gauge), signal conditioners, a data acquisition system, data storage and a processing system.

7.2.5.2 Sensor requirements

7.2.5.2.1 Accelerometers

a) The sensitivity and range of the accelerometers shall consider the response size of the measured component and background noise.

b) Accelerometers in different weight shall be chosen according to the local stiffness and weight of the measured part to reduce the influence of additional mass.

c) The lateral sensitivity of the accelerometer shall not be greater than 5 % of the sensitivity in the spindle direction.

d) The deviations from amplitude linearity of the accelerometer shall not be greater than 1 % in the experimental range.

7.2.5.2.2 Strain gauge

To measure the strain, the gauge’s form, size, range and accuracy shall be selected according to test purpose. The cables used shall be low noise cables.

7.2.5.3 Installation of sensors

The installation and routing of the sensor shall neither impose additional restrictions on the test specimen, nor modify the response characteristics of the product.

7.2.5.4 Signal conditioners

a) The filter of the signal conditioners shall have linear phase-shifting characteristics. The error in the experimental frequency range shall be within ±1 dB;

b) The amplitude linearity shall not be greater than 1 %.

c) The signal conditioners shall have the function of signal calculation for force signal regulators, including calculation function of resultant force, splitting moment and resultant moment, and gain attenuation setting of output signals.

7.2.5.5 Data acquisition and processing system

a) The data acquisition system shall be able to acquire signals of accelerometers, strain gauges and other required sensors.

b) The data acquisition system shall have sinusoidal vibration and random vibration data acquisition modules, with functions of real-time data acquisition, recording, processing and analysis.

c) The data acquisition system shall have enough measurement channels to meet the requirements of the customer.

d) Measurement uncertainties shall meet the requirements of the customer.

8 Test procedure

8.1 Test preparation

8.1.1 Preparation of the test documents

The test documents shall be prepared according to ISO 15864:2021, 4.9. The test documents shall be reviewed by the customer. Before starting a test, the test plan shall be reviewed to determine test specimen configuration(s), levels, durations, vibration exciter control strategy, item operational requirements, instrumentation requirements, facility capability and fixture.

a) Appropriate vibration exciters and fixtures shall be selected.

b) An appropriate data acquisition system composition (e.g. instrumentation, cables, signal conditioning, recording and analysis equipment) shall be selected.

c) The vibration equipment shall be operated without the test specimen installed to confirm proper operation.

d) The data acquisition system functions shall be ensured as required.

e) If FLVT is applied, the structure analysis results (resonance frequencies, modal effective mass, etc), interface conditions (materials, masses, parts, etc.), quasi-static loads, flight limit loads and design loads shall be specified.

8.1.2 Check of test equipment and test specimen

Check shall be performed before test conduction. If not specified otherwise, the following requirements apply.

a) The test setup shall be as specified in the test requirements.

b) It shall be ensured that the performance capability of the test equipment meets the test requirements.

c) All the test equipment shall be calibrated and used in the valid period.

d) The test specimens shall be examined for physical defects.

e) The test specimen shall be configured for test, in its operating configuration if required, as specified in the test plan.

f) The test specimen/fixture/exciter combination shall be examined for compliance with test specimen and test plan requirements.

g) An operational checkout shall be conducted in accordance with the test plan and the results shall be conducted for comparison with data taken during or after the test.

8.1.3 Safety check

The safety check shall be in accordance with ISO 19924:2017, 9.2.1.3.

8.2 Test implementation

8.2.1 General

Vibration testing on spacecraft system level is generally conducted in each of the three orthogonal directions. For each test, the test implementation shall consider the following sequence.

8.2.2 Before test

a) The test specimen shall be mounted to the fixture according to the required test direction. If the static load of the vibration system cannot meet the requirements, an auxiliary flexible support may be installed after customer approval.

b) The control transducers shall be installed on fixture as required.

c) A visual inspection and a functional test of the specimen shall be performed.

d) The parameters of the control and measurement systems shall be set, and the readiness of all systems for the test shall be verified.

e) A pre-test shall be performed to measure the structure response and to check the control and measurement systems.

8.2.3 During test

a) If not specified otherwise, the following test sequence shall be performed. A low-level pre -test shall be performed. The test shall be carried out according to the test level conditions specified in the test specification. The structural response shall be recorded and, if required, the test specimen performance shall be monitored during the test. After completing the test, all data shall be analysed to determine the conditions of full level vibration testing, such as notching requirement and response limit profile.

b) A full-level vibration testing shall be performed. Structural responses shall be recorded and, if required, the test specimen performance shall be monitored. After the test, the connecting screws between the test specimen and the fixture shall be checked to ensure that connecting screws are not loose.

c) A low-level vibration testing shall be performed again. After the test, both low-level testing results shall be evaluated to evaluate the test specimen integrity by comparing its resonance frequencies and amplification factors.

If the test plan calls for additional intermediate or full-level testing, steps a) through c) shall be repeated as required by the test plan before proceeding.

A low-level sweep down sine test should be performed in case of suspicion of nonlinear behaviour, or unexpected behaviour during sweep up test.

8.2.4 After test

a) After the completion of testing in one direction, a visual inspection of the test specimen shall be performed. Functional and electrical performance tests shall be conducted if necessary.

b) In case failures, structural degradation or other anomalies are found during the test, the test interruption and handling requirements shall be considered.

9 Test interruption and handling

9.1 Test interruption

If either of the following situations appears, the test shall be interrupted:

a) laboratory equipment malfunctions;

b) the technical requirements cannot be met due to exceeding test tolerances;

c) test specimen operation failure.

9.2 Interruption handling

Test interruption should be handled as follows.

a) If a test is interrupted because of test equipment malfunction, the test shall only be continued after the failure had been eliminated and it is made sure there is no effect on the specimen.

b) If a test is interrupted because the technical requirements cannot be met due to exceeding test tolerances, after eliminating the reason the parameters shall be reset and the test shall be performed again. In case of under-testing, test results acquired before the interruption shall be considered invalid. In case of over-testing, it shall be ensured there was no effect on the specimen and the test may be restarted from the interruption point (in that case, of the total duration before and after the interruption shall be considered as test duration).

c) If a test is interrupted because of test specimen operation failure, the test shall only be continued after the interference or failure had been eliminated.

10 Test data and result evaluation

10.1 Test data

Typically, vibration testing data includes the following items:

a) control results of the test;

b) structure response of the test specimen in the frequency domain, and, if specified in the contract requirement, in the time domain;

c) environment data of laboratory;

d) status data of the equipment;

e) status data of the test specimen.

Test data requirements shall conform to ISO 15864:2021, 4.9.5.

10.2 Result evaluation

After test, the results shall be evaluated according to the following criteria:

a) conformance of the control results with the test requirements;

b) conformance of the measurement results with the test requirements;

c) conformance of the overall results with the test objectives.

11 Test reports

Test documentation shall conform to ISO 15864:2021, 4.9.

Annex A
(Informative)

A method for random vibration and acoustic test tailoring

Because of the differences between random vibration and acoustic test, if it is possible, combined random vibration and acoustic testing should be performed. Otherwise, either vibration or acoustic testing should be selected to conduct, whichever is more appropriate, with the other one left optional. In the selection of a random vibration testing method or acoustic test method, the "break even" area/mass ratio[20,21] of a test object is important.

One method of "break even" area/mass ratio will be calculated by X-Y-F formula:

$$\left[\frac{S}{m}\right]_\mathrm{b} = X_\mathrm{e} \times \sqrt{\frac{\Delta f \cdot R(f)}{P_\mathrm{ref}^2 \cdot 10^{\frac{A(f)}{10}}}} \tag{A.1}$$

where

$\left[\frac{S}{m}\right]_\mathrm{b}$	is the "break even" area/mass ratio;
$R(f)$	is the PSD of random vibration testing reference spectrum at f;
f	is the frequency where test specimen has maximum response in testing;
$A(f)$	is the sound pressure level at f;
P_ref	is reference sound pressure, $P_{ref} = 2 \times 10^{-5} Pa$;
Δf	is bandwidth, for 1/1 octave bandwidth $\Delta f = 0.707 f_c$, 1/3 octave bandwidth $\Delta f = 0.232 f_c$;
X_e	is correction coefficient:

$$X_\mathrm{e} = \frac{\beta_r}{\beta_a} \tag{A.2}$$

$$\beta_a = \sqrt{\frac{W(f)_\text{A-max}}{Q^2 \left(\frac{A}{M}\right)^2 P_\mathrm{s}}} \tag{A.3}$$

$$\beta_r = \sqrt{\frac{W(f)_\text{R-max}}{Q^2 R(f)}} \tag{A.4}$$

$$P_\mathrm{s} = P_\mathrm{ref}^2 \cdot 10^{\frac{A(f)}{10}} / \Delta f \tag{A.5}$$

where

$W(f)_\text{A-max}$	is the average response in acoustic test or analysis;
$W(f)_\text{r-max}$	is the average response in random vibration testing or analysis;
P_s	is the sound pressure;

Q is the quality factor;

A is the sound pressure excitation surface area, e.g. the top and sides surface area of a specimen;

M is the mass of test specimen.

$W(f)_{\text{A-max}}$ and $W(f)_{\text{r-max}}$ should be used the test data of similar structure test specimen or simulation analysis results.

EXAMPLE The acoustic and random vibration testing reference spectrums of SAT-1 are show in Table A.1 and Table A.2. The sound pressure level at 250 Hz with 1/1 octave band is 134 dB, the random vibration testing PSD is 0,031 g^2/Hz from 150 Hz to 800 Hz, which is 2,98 $(m/s^2)^2$/Hz.

a) Calculate β_a, selecting the key response point of the SAT-1 in acoustic testing, as shown in Table A.3.

For point 1:

$$\beta_{a-1} = \sqrt{\frac{1{,}0187}{4{,}5^2 \times 0{,}018^2 \times 28{,}42}} = 2{,}337 \tag{A.6}$$

β_a is the average value which equals to 2,658.

b) Calculate β_r, as shown in Table A.4.

For point 1:

$$\beta_{r-1} = \sqrt{\frac{0{,}101}{4{,}5^2 \times 0{,}031}} = 0{,}401 \tag{A.7}$$

β_r is the average value which equals to 0,402.

c) The "break even" area/mass ratio:

$$\left[\frac{s}{m}\right]_{\text{b}} = \frac{0{,}402}{2{,}658} \times \sqrt{\frac{0{,}707 \times 250 \times 2{,}98}{4 \times 10^{3{,}4}}} = 0{,}0346 \tag{A.8}$$

d) The surface-mass ratio is 0,018, which is less than 0,034, so the random vibration should be recommended.

Table A.1 — Random vibration testing level

Frequency (Hz)	20 to 150	150 to 800	800 to 2 000
reference PSD	+3 dB/Oct	0,031 g^2/Hz	−6 dB/Oct

Table A.2 — Acoustic testing level

1/1 octave centre frequency f_c (Hz)	31,5	63	125	250	500	1 000	2 000	4 000	8 000
Test level (dB)	116	122	130	134	136	133	125	121	114

Table A.3 — Key points response of SAT-1 in acoustic testing

Point	Q	f	f_c	$A(f)$	P_s	W_{A-max}	A/M	β_{a-i}
1	4,5	272	250	134	28,42	1,018 7	0,018	2,337
2	4,5	272	250	134	28,42	0,489 3	0,018	1,620
3	4,5	204	250	134	28,42	0,26	0,018	1,375
4	4,5	212	250	134	28,42	0,436 4	0,018	1,538

Table A.3 *(continued)*

Point	Q	f	f_c	$A(f)$	P_s	W_{A-max}	A/M	β_{a-i}
5	4,5	632	500	136	22,52	4,279 8	0,018	5,381
β_a								2,658

Table A.4 — Key points response of SAT-1 in random vibration testing

Point	Q	$R(f)$	W_{r-max}	β_{r-i}
1	4,5	0,031	0,101	0,401
2	4,5	0,031	0,033 7	0,232
3	4,5	0,031	0,097 9	0,395
4	4,5	0,031	0,159 6	0,504
5	4,5	0,031	0,144 7	0,480
β_r				0,402

Annex B
(Informative)

An example of notching principles and calculation method for notching control

B.1 This annex applies only to spacecraft as it requires the results of the coupling analysis between spacecraft and rocket. An example of notching principles and calculation method for notching control is given in B.2 to B.4.

B.2 The force of the main structure is required to be not higher than the design value of quasi-static load[22].

a) For spacecraft, in the case of an interface ring, the maximum force per unit of length $F_{\max 0}$ of main structure under static load is calculated as shown in Formula (B.1):

$$F_{\max 0} = \frac{M}{2\pi R} A_{\mathrm{A}0} + \frac{MH_{\mathrm{c}}}{\pi R^2} A_{\mathrm{L}0} \tag{B.1}$$

where

M is the mass of spacecraft;

R is the radius of the interface of the spacecraft and the rocket;

H_{c} is the height of centroid;

$A_{\mathrm{A}0}$ is the acceleration of axial direction;

$A_{\mathrm{L}0}$ is the acceleration of transverse direction

b) The maximum counterforce $F_{\max\mathrm{A}}$, $F_{\max\mathrm{L}}$ of main structure during vibration testing is calculated as shown in Formula (B.2) and Formula (B.3):

For axial direction vibration:

$$F_{\max\mathrm{A}} = \beta_{\mathrm{A}} \frac{M}{2\pi R} A_{\mathrm{A}} \tag{B.2}$$

For transverse direction vibration:

$$F_{\max\mathrm{L}} = \beta_{\mathrm{L}} \frac{H_{\mathrm{c}} M}{\pi R^2} A_{\mathrm{L}} \tag{B.3}$$

where

β_A is the factor of counterforce at the interface between spacecraft and fixture in axial direction vibration, it is calculated as shown in Formula (B.4);

β_L is the factor of counterforce at the interface between spacecraft and fixture in transverse direction vibration, it is calculated as shown in Formula (B.4);

A_A is the vibration acceleration level of axial direction vibration;

A_L is the vibration acceleration level of transverse direction vibration.

$$\beta_A(f)=\frac{F_A(f)}{F_{Ac}} \text{ or } \beta_L(f)=\frac{F_L(f)}{F_{Lc}} \tag{B.4}$$

where

f is the frequency where test specimen has maximum response in testing;

$F_A(f), F_L(f)$ are counterforce between spacecraft and fixture at f;

F_{Ac}, F_{Lc} are counterforce between spacecraft and fixture at lower frequency (normally the beginning frequency of the test).

c) It is requested that $F_{\max A} \le F_{\max 0}$ and $F_{\max L} \le F_{\max 0}$.

B.3 The vibration level is required to be more than the level of coupling analysis result between spacecraft and rocket[23].

B.4 In case of linear behaviour of the test specimen during vibration tests, response of key equipment fixed position is required not to be higher than the equipment vibration testing level.

$$a_{H\_i}(f) \le \frac{a_i^S(f)}{a_i^L(f)} a_L(f) \tag{B.5}$$

where

$a_i^L(f)$ is the response of key equipment fixed position at signature test level;

$a_L(f)$ is the signature test level;

$a_i^S(f)$ is the key equipment's vibration testing level;

$a_{H\_i}(f)$ is the response of key equipment fixed position at full test level.

If there is multiple key equipment, the requirement is

$$a_S(f) \le \min_{i=1,2,L,n} \left(a_{H\_i}(f)\right) \tag{B.6}$$

where

n is the number of key equipment.

Annex C
(informative)

Force limit determination

C.1 General

To implement force limited vibration testing, force limits must be determined properly which can replicate the force response of the test specimen in flight configuration. Force limits can be determined in different ways depending on the available information on the test specimen. Five methods for designing force limits are introduced briefly in this annex.

C.2 Analytical methods using two-degree of freedom system model

C.2.1 General

The force limits design strategy using two-degree of freedom system model can be described in the following steps:

a) establishment of a two-degree of freedom system (TDFS) model containing a source (the mounting structure or the launch vehicle) and a load (the test specimen);

b) determination of the mechanical parameters of the TDFS model; the apparent masses [defined by Formula (C.1)] of the source and the load can be estimated by FEA or measured experimentally;

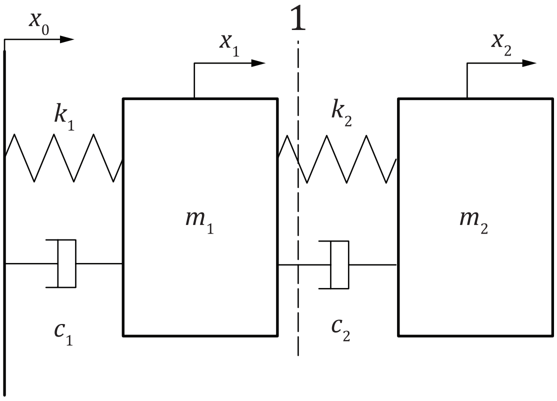
c) solution of the coupled system to obtain the accelerance (complex frequency response function which is ratio of acceleration to force) of the interface;

d) derivation of force limits according to the acceleration specification and the accelerance obtained in step c).

The TDFS method can be classified into two categories, the simple TDFS method and the complex TDFS method, according to the adopted coupled models.

C.2.2 Simple TDFS method

The source and the load are simplified as two masses in the simple TDFS method as shown in Figure C.1.



Key

1 interface

x_0 the displacement of the base

x_1 the displacement of the source

x_2 the displacement of the load

m_1 the mass of the source

m_2 the mass of the load

k_1 the stiffness of the source

c_1 the damping of the source

k_2 the stiffness of the load

c_2 the damping of the load

Figure C.1 — The simple TDFS model

The apparent mass $M(\omega)$ at the interface is given by:

$$M(\omega)=\frac{F(\omega)}{A(\omega)}=m_2\frac{1+j2\xi_2\dfrac{\omega}{\omega_2}}{\left[1-\left(\dfrac{\omega}{\omega_2}\right)^2\right]+j2\xi_2\dfrac{\omega}{\omega_2}} \tag{C.1}$$

where

$F(\omega)$ is the force at the interface;

$A(\omega)$ is the acceleration at the interface;

ω is the excitation frequency;

ω_2 is the natural frequency of the load;

ξ_2 is the modal damping of the load.

The load acts as a classical dynamic absorber at the natural frequency of the coupled system illustrated in Figure C.1. When the natural frequency of the load coincides with the natural frequency of the source (denoted as ω_0), the acceleration responses of the source and the load both reach their maximum values and the force at the interface also reaches its peak value. For this case, the characteristic formula is given by:

$$(\omega/\omega_0)^2 = 1 + \frac{1}{2}\frac{m_2}{m_1} \pm \sqrt{\frac{m_2}{m_1} + \frac{1}{4}\left(\frac{m_2}{m_1}\right)^2} \tag{C.2}$$

The ratio of the interface force to acceleration spectral densities normalized by the magnitude squared of the load mass is then obtained.

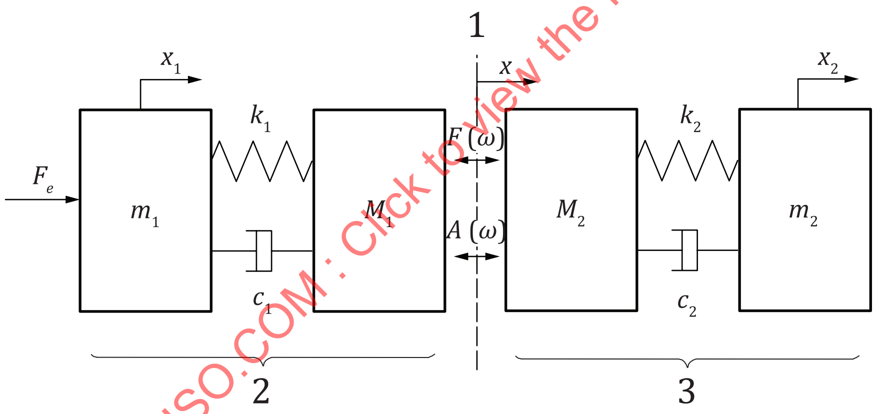
$$\frac{S_{\mathrm{FF}}}{S_{\mathrm{AA}} m_2^2} = \frac{1 + (\omega/\omega_0)^2 / Q_2^2}{[1 - (\omega/\omega_0)^2]^2 + (\omega/\omega_0)^2 / Q_2^2} \tag{C.3}$$

where

S_{FF}	is the interface force spectral density;
S_{AA}	is the interface acceleration spectral density;
$Q_2 = 1/(2\zeta_2)$	is the quality factor of the load, with ζ_2 is the damping ratio of the load;

C.2.3 Complex TDFS method

In the complex TDFS model shown in Figure C.2, the source and load each have two masses to represent both the residual and modal masses of a continuous system.



Key

1	interface	M_1	the residual mass of the source
2	the source	M_2	the residual mass of the load
3	the load	k_1	the model stiffness of the source
x	the displacement of the interface	c_1	the model damping of the source
x_1	the displacement of the source	k_2	the model stiffness of the load
x_2	the displacement of the load	c_2	the model damping of the load
m_1	the model mass of the source	$F(\omega)$	the force at the interface
m_2	the model mass of the load	$A(\omega)$	the acceleration at the interface

Figure C.2 — The complex TDFS model