INTERNATIONAL STANDARD

**ISO 10813-4**

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# Vibration generating machines — Guidance for selection —

## Part 4: Equipment for multi-axial environmental testing

*Générateurs de vibrations — Lignes directrices pour la sélection —*

*Partie 4: Équipement pour les essais environnementaux multi-axiaux*



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# Foreword

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

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

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

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For an explanation on 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 the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 6, *Vibration and shock generating systems*.

A list of all parts in the ISO 10813 series can be found on the ISO website.

# Introduction

Selection of a suitable vibration generating system is an urgent problem as one needs to purchase new test equipment or to update the equipment already at one's disposal to perform a certain test or to choose from among the equipment proposed by a test laboratory or even a laboratory itself which offers its service to carry out such a test. A problem like this can be resolved only if a number of factors are considered simultaneously, as follows:

— type of test to be carried out (environmental testing, normal and/or accelerated, dynamic structural testing, diagnosis, calibration, etc.);

— requirements to be followed;

— test conditions (single or multiple excitation, one mode of vibration or combined vibration, single or combined test, for example, dynamic plus climatic, etc.);

— objects to be tested.

This document deals only with equipment to be used for multi-axial environmental testing, and procedures of the selection are predominant to meet the requirements of this testing.

Because the multi-axial environmental test system is composed of more than one exciter, ISO 10813-1 should be used along with this document to select the proper exciters. It is presumed in this document that the system to be selected will be able to drive the object under test up to a specified level. In order to generate an excitation without undesired motions, a suitable control system should be used, however selection of a control system lays beyond the scope of this document.

It should be emphasized that vibration generating systems are complex machines, so the correct selection always demands a certain degree of engineering judgement. As a consequence the purchaser, when selecting the vibration test equipment, may resort to the help of a third party. In such a case, this document can help the purchaser to ascertain if the solution proposed by the third party is acceptable or not. Designers and manufacturers can also use this document to assess the market environment.



# Vibration generating machines — Guidance for selection —

# Part 4: Equipment for multi-axial environmental testing

## 1 Scope

This document gives guidance for the selection of vibration generating equipment for multi-axial environmental testing, depending on the test requirements.

Multi-axial environmental test equipment dealt with in this document refers to a vibration test system having controlled vibration of more than one degree of freedom, including linear vibration and angular vibration. In this document, one or more exciter per desired degree of freedom is supposed.

The guidance covers such aspects of selection as

— number, type and models of exciters,

— number, type and models of connectors,

— system configuration, and

— some components.

## 2 Normative references

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

ISO 2041, *Mechanical vibration, shock and condition monitoring — Vocabulary*

ISO 10813-1, *Vibration generating machines — Guidance for selection — Part 1: Equipment for environmental testing*

ISO 15261, *Vibration and shock generating systems — Vocabulary*

## 3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and ISO 15261 and the following apply.

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

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

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

**3.1**
**exciter**
**vibration generator**
excitation source where vibratory forces are generated

**3.2**
**table**
platform on which specimens or fixtures are mounted

**3.3**
**multi-exciter system**
vibration generating system which includes two or more *exciters* (3.1) and a control system to coordinate the motion

**3.4**
**connector**
device used to transmit the excitation force from *exciters* (3.1) to the *table* (3.2) or specimens with the capability of decoupling the linear motions between *exciters* (3.1)

**3.5**
**spherical connector**
*connector* (3.4) with spherical joints

Note 1 to entry: Normally spherical connector has one or two spherical joints (see Figure 7).

**3.6**
**planar connector**
*connector* (3.4) having planar restriction which is capable of moving in two orthogonal axes in that plane

Note 1 to entry: Some planar connectors also have another single-degree-of-freedom (1-DOF) rotational motion in the plane.

**3.7**
**drive rod**
**stinger**
rod with a large length-diameter ratio, stiff in the longitudinal direction and flexible in the transverse direction

**3.8**
**parasitic motion**
undesired motion of the *table* (3.2) that occurs when multi-axial excitation is carried out over the *table* (3.2)

**3.9**
**guidance system**
mechanical device used to guide the *exciter* (3.1) to move in the axial direction, providing transverse motion restraint to the *exciter* (3.1)



# 4 Requirements for multi-axial environmental tests

## 4.1 Multi-axial vibration test motivation

In the real world, pure single axis vibration does not exist, meaning that the real vibration environment is multi-axial. However due to test equipment restrictions, multi-axial vibration testing is mainly conducted one axis after another sequentially, which has different impacts on the specimens than multi-axial simultaneous vibration tests. It is reported that some devices failed in the real multi-axial environment after single axis vibration testing was conducted with no abnormities observed. Therefore, to simulate the real vibration environment and help discover the product malfunction rationale due to multi-axial vibration, the need to conduct a real multi-axial vibration testing has been growing dramatically.

The most common reasons to conduct a multi-axial vibration test are listed below[4][5]:

- Distributed multi-axial vibration or shock energy is applied over the specimen in a controlled manner without relying on the dynamics of the specimens for such distribution.
- Multi-axial testing can be selected when the specimen has a high slenderness ratio for energy distribution considerations.
- Multi-exciter system is selected to increase the thrust force in order to achieve the desired vibration level for large and heavy specimens.
- Some multi-axial vibration test systems are constructed to increase the overall test efficiency because the tests of different axes can be conducted simultaneously rather than sequentially.
- Multi-axial vibration testing is conducted on inertial measurement units which are subject to linear and angular vibration and the measuring accuracy is highly dependent on the multi-axial environment.
- Multi-axial vibration testing is conducted in several directions rotationally or translationally to meet test criteria or to reproduce in-service measurement data, such as automotive or earthquake simulations.
- Multi-axial vibration testing can be selected to avoid the need to design and fabricate a very expensive fixture that may be used only once.
- Multi-axial vibration testing can be selected to provide a compensating force to counteract large overturning moments, which may occur during testing of tall structures, such as satellites with several meters of height of centre of gravity.

## 4.2 Test waveforms

Multi-axial vibration testing mainly deals with the following waveforms:

- wide-band random;
- time history waveform replication.

NOTE Sinusoidal testing, including swept and fixed frequency sinusoidal testing, is not common in practice for multi-axial configuration, but is achievable.

## 4.3 Types of multi-axial environmental testing

### 4.3.1 General

Typical multi-axial environmental vibration testing includes the following types.

### 4.3.2 Parallel thrust testing

Parallel thrust testing is used to excite one specimen at multiple points in parallel directions. The purpose is to simulate the real multi-excitation parallel working environment. Typical tests include automobile vibration testing through four wheels under independent excitations and missile vibration testing through dual excitation points.

### 4.3.3 Bi-axial vibration testing

The purpose of bi-axial vibration testing is to excite the specimen from two orthogonal directions. It is a simplified condition of tri-axial vibration testing, which is suitable when the specimen is firmly constrained in one direction and therefore the vibration in that direction has little impact. The two orthogonal directions can be two horizontal directions or one horizontal and one vertical direction.



#### 4.3.4 Tri-axial vibration testing

The purpose of tri-axial vibration testing is to excite the specimen from three orthogonal directions to simulate the actual tri-axial vibration environment for most real-world objects when rotational excitations are not considered.

#### 4.3.5 Six-degrees-of-freedom vibration testing

The purpose of six-degrees-of-freedom (6-DOF) vibration testing is to simulate a complete 6-DOF spatial vibration of a specimen, including three-degrees-of-freedom (3-DOF) of linear vibration and 3-DOF of angular vibration. It is useful for specimens which are sensitive to angular vibration such as inertial measurement units.

#### 4.3.6 Other multi-degrees-of -freedom testing

Depending on conditions of the actual vibration environment, any number of degrees of freedom (DOFs), but no less than 2 and no more than 6 per excitation point, may be required to conduct the test.

## 5 Multi-axial vibration test equipment

### 5.1 Types of multi-axial vibration test equipment

#### 5.1.1 General

In order to meet various multi-axial vibration testing requirements, many kinds of test equipment have been developed. Typical types of multi-axial vibration test equipment are listed in 5.1.2 to 5.1.6.

#### 5.1.2 Parallel thrust equipment

In order to produce the force required for a test which cannot be satisfied by single exciters or to adapt to testing slender specimens, multiple exciters are aligned in parallel. The exciters can be controlled in or out of synchronization or completely independently. Angular vibration can be generated when exciters are driven at different amplitudes or phases. The selection of an amplitude and phase synchronized multi-exciter test system can be considered as the selection of a single vibration generator (see ISO 10813-1), and is therefore not included in this document. Figure 1 shows an example of a parallel thrust configuration in which a slender specimen is excited vertically by two independent exciters at two excitation points with connectors decoupling motion contradictions brought about by exciter asynchrony. A suspension device is applied to offset the specimen mass.

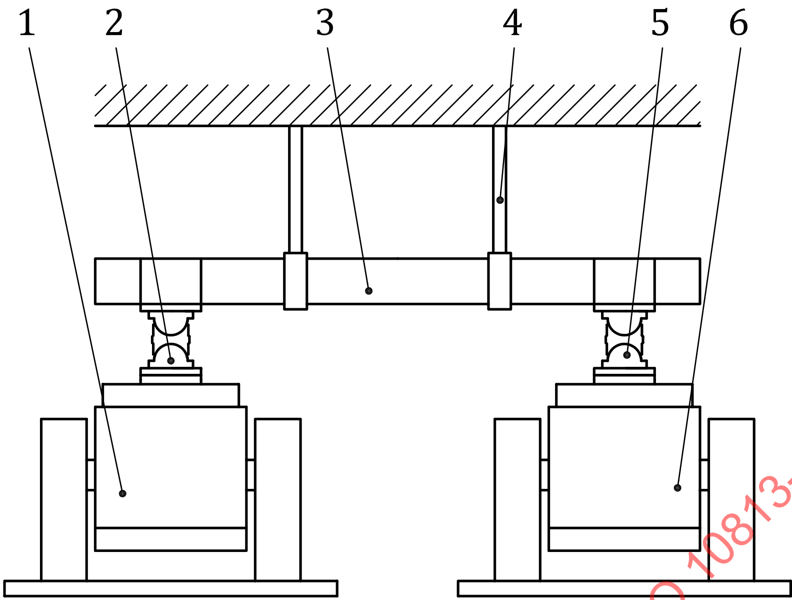
#### 5.1.3 Bi-axial linear vibration equipment

Bi-axial linear vibration equipment is composed of two exciters in orthogonal coordinates. Linear vibration testing in two orthogonal directions can be generated simultaneously and angular vibration test cannot be performed. Figure 2 shows an example of a bi-axial linear vibration configuration, in which two exciters are arranged in a vertical/horizontal manner. The table is linked with the two exciters through the two connectors. Adapters can be employed when necessary to couple the table with the connectors.

NOTE There are occasions when two exciters are not available or it is too expensive to construct a real bi-axial test system. “Bi-axial” testing can be conducted by a one exciter configuration, in which the axis of the exciter is at a specific angle, i.e. 45°, with respect to the two concerning axes. This method is essentially a single axis test but can be taken as a synchronized bi-axial test as well. See IEC 60068-3-3[3] for a detailed description of this method.



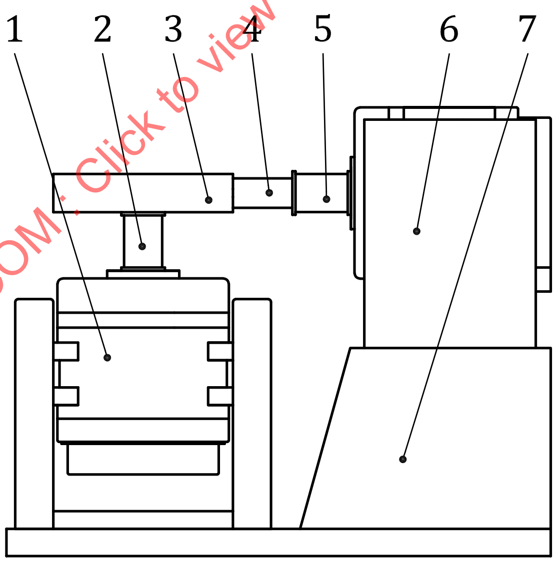
 




**Key**

| | | | |
|---|---|---|---|
| 1 | exciter 1 | 4 | suspension |
| 2 | connector 1 | 5 | connector 2 |
| 3 | specimen | 6 | exciter 2 |

**Figure 1 — Example of parallel thrust equipment**



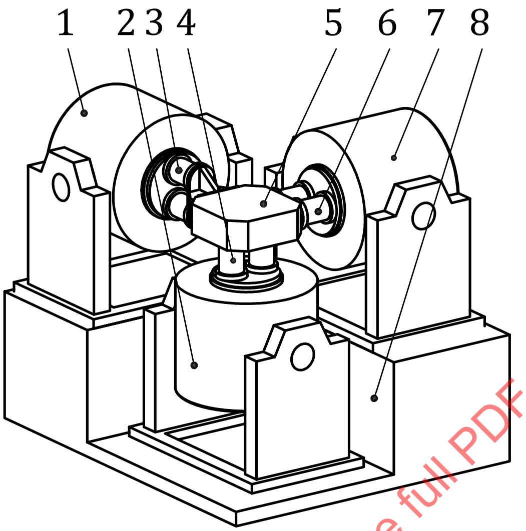

**Key**

| | | | |
|---|---|---|---|
| 1 | exciter 1 | 5 | connector 2 |
| 2 | connector 1 | 6 | exciter 2 |
| 3 | table | 7 | pedestal |
| 4 | adaptor | | |

**Figure 2 — Example of bi-axial linear vibration equipment**

### 5.1.4 Tri-axial linear vibration equipment

Tri-axial linear vibration equipment is composed of many exciters in three orthogonal coordinates. Simultaneous rectilinear vibrations in three orthogonal directions can be generated and angular vibration test cannot be performed. Figure 3 shows an example of a tri-axial linear vibration configuration, in which three exciters are arranged in a Cartesian coordinate. In this example, 6 dual sphere connectors are used to decouple the table motion and restrain unwanted motions. Air spring isolations are placed between the equipment and the ground to reduce vibration transmission to the laboratory.




**Key**

| | | | |
|---|---|---|---|
| 1 | exciter 1 | 5 | table |
| 2 | exciter 2 | 6 | connectors 3' and 3'' |
| 3 | connectors 1' and 1'' | 7 | exciter 3 |
| 4 | connectors 2' and 2'' | 8 | pedestal |

**Figure 3 — Example of three-exciters in orthogonal coordinate configuration**



NOTE There are occasions when more than two exciters are not available or it is too expensive to construct a real tri-axial test system. "Tri-axial" testing can be conducted by two exciter configurations, in which one exciter is vertically assigned and the other is horizontally assigned. This method is essentially a bi-axial test but can be taken as a synchronized tri-axial test as well. See IEC 60068-3-3 for a detailed description of this method.

### 5.1.5 Six-degrees-of-freedom test equipment

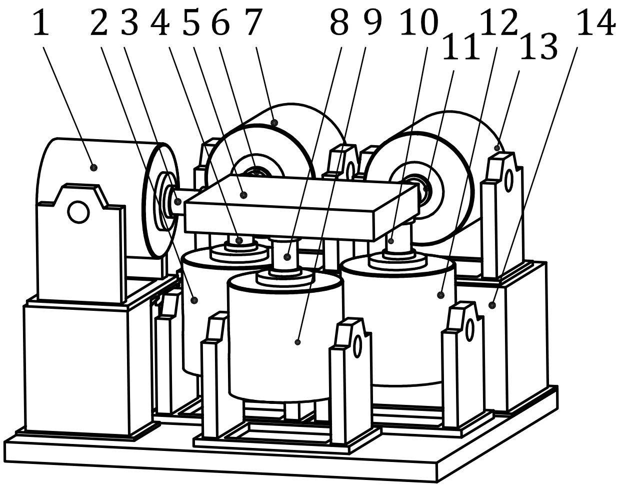
The 6-DOF test equipment is composed of no less than six exciters. At least two exciters are required to act in parallel to generate an angular vibration. The basic motion 6-DOF equipment can generate includes linear vibration in the three orthogonal axes and three angular vibrations about the orthogonal axes. By controlling the basic motion properly, spatial in-axis or out-of-axis translational and rotational vibration can be generated.

Typical 6-DOF test systems can be configured as follows:

— System composed of 6 exciters in orthogonal coordinate with three exciters in the vertical direction, other three exciters in horizontal directions (two in X axis, one in Y axis), shown in Figure 4.

— System composed of 8 exciters in orthogonal coordinate with four exciters in the vertical direction, other four exciters in horizontal directions (two for each axis), shown in Figure 5.

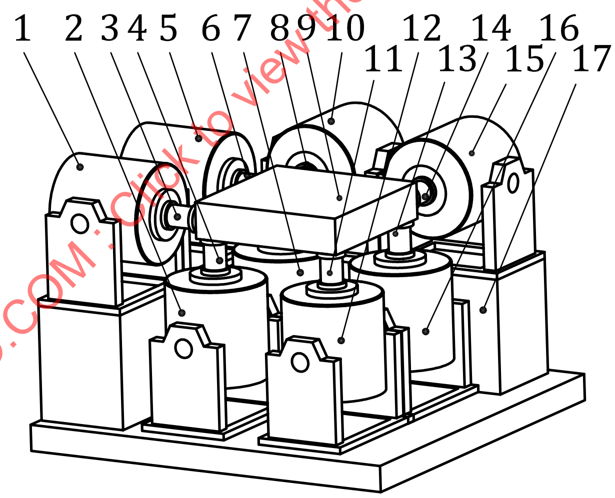
 




**Key**

1 exciter 1
2 exciter 2
3 connector 1
4 connector 2
5 table
6 connector 3
7 exciter 3
8 connector 4
9 exciter 4
10 connector 5
11 connector 6
12 exciter 5
13 exciter 6
14 pedestal

**Figure 4 — Example of a 6-DOF vibration system composed of 6 exciters and 6 connectors**




**Key**

1 exciter 1
2 exciter 2
3 connector 1
4 connector 2
5 exciter 3
6 connector 3
7 exciter 4
8 connector 5
9 table
10 exciter 5
11 connector 6
12 exciter 6
13 connector 7
14 connector 8
15 exciter 8
16 exciter 7
17 pedestal

NOTE Connector 4 is hidden.

**Figure 5 — Example of a 6-DOF vibration system composed of 8 exciters and 8 connectors**

NOTE The exciters can be any type in practice although the examples given in Figures 1 to 5 take electrodynamic vibration generators as exciters.

### 5.1.6 Other multi-axial test equipment

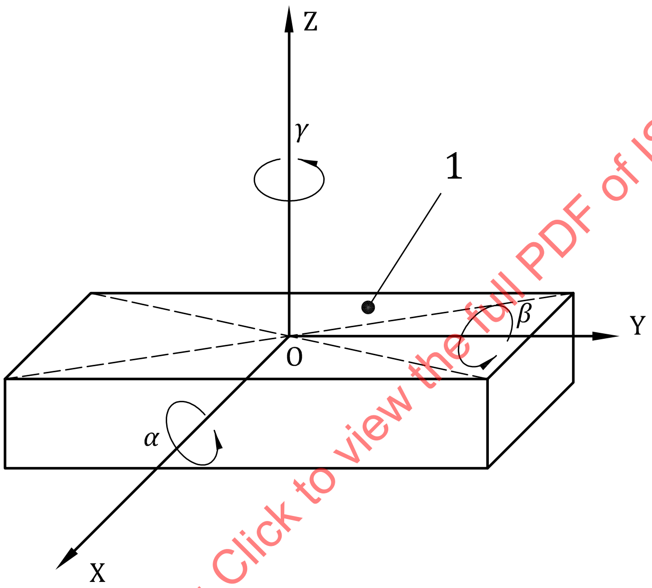
Other multi-axial test equipment can be constructed to meet special testing requirements.

There are also some special multi-axial test systems. For instance, a system in which the coordinate plane of the exciters and the coordinate plane of the table are neither parallel nor perpendicular can generate a multi-axial testing environment in accordance with a special axis system. For example, a Stewart platform is a typical 6-DOF motion platform, which is composed of 6 exciters arranged with a special angle, neither parallel nor perpendicular, with the table coordinates.

NOTE Consult manufacturers for special multi-axial system requirements.

## 5.2 Coordinate system

See Figure 6.




**Key**

1 table

X, Y horizontal axes

Z vertical axis

*α* rotation about the X axis

*β* rotation about the Y axis

*γ* rotation about the Z axis

O centre point on the surface of the table in geometry

NOTE The centre of gravity of the table (point C) is not shown in the figure. Axes X, Y, Z form a Cartesian coordinate system.

**Figure 6 — Coordinate system of a multi-axial system**

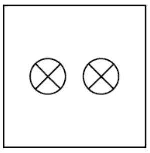
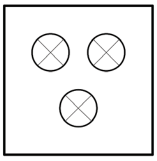
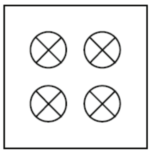
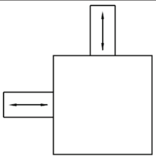
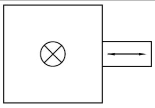
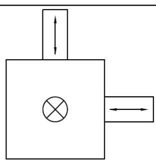
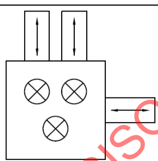
## 5.3 Typical configurations for multi-axial testing

Typical configurations of a multi-axial vibration test system can be found in Table 1. The "Conf. Code" is unique to every configuration so that the code can be used to represent the arrangement of exciters.



**Table 1 — Typical configuration of multi-axial vibration test system**

| Conf. Code | Graphical representation [a] | Description | $N_t$ | $N_l$ | $N_a$ | $N_e$ |
|---|---|---|---|---|---|---|
| C1 |  | Two exciters in parallel. | 2 | 1 | 1 | 2 |
| C2 |  | Three exciters in parallel. 2-DOF of angular vibration can be achieved when exciters are driven out of phase. | 3 | 1 | 2 | 3 |
| C3 |  | Four exciters in parallel. 2-DOF of angular vibration can be achieved when exciters are driven out of phase. | 3 | 1 | 2 | 4 |
| C4 |  | Two exciters in orthogonal directions, horizontally assigned. | 2 | 2 | 0 | 2 |
| C5 |  | Two exciters in orthogonal directions, one horizontally and one vertically assigned. | 2 | 2 | 0 | 2 |
| C6 |  | Three exciters in orthogonal directions. | 3 | 3 | 0 | 3 |
| C7 |  | One exciter in Y[b] axis, providing linear motion along Y axis; Two exciters in X axis, providing linear motion along X axis and rotation about Z axis; Three exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axes. | 6 | 3 | 3 | 6 |

**Key**

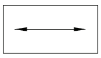
$N_t$: Number of total DOFs (see 7.3).

$N_l$: Number of linear DOFs (see 7.3).

$N_a$: Number of angular DOFs (see 7.3).

$N_e$: Number of exciters (see 7.2).

[a] The graphical representation is an abbreviated view of the multi-axial vibration test equipment looking upward from the bottom. The connectors are not shown in this representation. The definition of the elements used in the graphical representation is as follows:



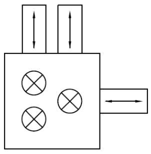
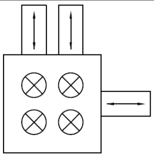
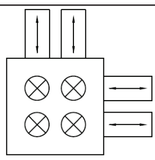
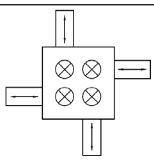
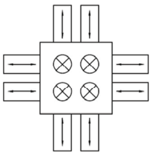
A horizontal exciter, including its associated connector.

A vertical exciter, including its associated connector.

The table, fixture or specimen from the bottom view.

[b] Axes X, Y, Z are according to Figure 6.

**Table 1** *(continued)*

| Conf. Code | Graphical representation [a] | Description | $N_t$ | $N_l$ | $N_a$ | $N_e$ |
|---|---|---|---|---|---|---|
| C8 |  | One exciter in Y axis, providing linear motion along Y axis; Two exciters in X axis, proving linear motion along X axis and rotation about Z axis; Three exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axes. | 6 | 3 | 3 | 6 |
| C9 |  | One exciter in Y axis, providing linear motion along Y axis; Two exciters in X axis, providing linear motion along X axis and rotation about Z axis; Four exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axes. | 6 | 3 | 3 | 7 |
| C10 |  | Two exciters each in X and Y axes, providing linear motion along X and Y axes and rotation about Z axis; Four exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axes. | 6 | 3 | 3 | 8 |
| C11 |  | Two exciters each in X and Y axes, providing linear motion along X and Y axes and rotation about Z axis; Four exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axes. | 6 | 3 | 3 | 8 |
| C12 |  | Four exciters in X and Y axis, providing linear motion along X and Y axis and rotation about Z axis; Four exciters in Z axis, providing linear motion in Z axis and rotation about X and Y axis. | 6 | 3 | 3 | 12 |

**Key**

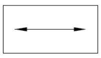
$N_t$: Number of total DOFs (see 7.3).

$N_l$: Number of linear DOFs (see 7.3).

$N_a$: Number of angular DOFs (see 7.3).

$N_e$: Number of exciters (see 7.2).

[a] The graphical representation is an abbreviated view of the multi-axial vibration test equipment looking upward from the bottom. The connectors are not shown in this representation. The definition of the elements used in the graphical representation is as follows:


A horizontal exciter, including its associated connector.


A vertical exciter, including its associated connector.


The table, fixture or specimen from the bottom view.

[b] Axes X, Y, Z are according to Figure 6.

## 6 Main components of multi-axial test equipment

### 6.1 Exciter

The most common types of exciters being used for multi-axial environmental testing are electrodynamic vibration generators and servo-hydraulic vibration generators.

Typically, electrodynamic vibration generators are suitable for higher frequencies with low waveform deformation, whereas servo-hydraulic vibration generators are suitable for long stroke and low frequency test conditions. Refer to ISO 10813-1 for detailed characteristics and selection procedures of electrodynamic vibration generators and servo-hydraulic vibration generators.

Other forms of exciters exist, such as mechanical vibration generators, electric servo cylinders or linear motors, which are not typical components of multi-axial vibration test systems. Selection of such exciters is not included in this document. Users may consult manufacturers regarding specific test requirements.

## 6.2 Table

The table is a platform on which the specimens or fixtures are mounted. The forces of the exciters merge in the table and are then transmitted to the specimens or fixtures. The table should be designed using modal analysis and optimization methods, with the aim of making the table low in mass and high in resonance frequency. This will make the table capable of working over a broader frequency range without consuming much vibration force. The table must be constructed in such a manner as to avoid undesired motions, particularly to be resistant to flexural deformation. An example of typical table parameters is given in Table 2.

Exciters coupled to the table normally provide a static suspension force. In some situations, extra suspension may be required. Typical situations include: 1) The load capacity of the table provided by exciters cannot satisfy the loading requirement of the test specimen; 2) The exciters cannot provide sufficient linear or rotational stiffness (see 7.4) to the table which may incur test failure.

Typical suspension solutions include the following: 1) air spring support (including air bags in a hydraulic cylinder); 2) steel spring support; 3) elastic cable hanging; 4) rubber. For example to increase the stiffness in the lateral direction for the case shown in Figure 3, springs (air spring or steel spring) can be affixed opposite of the two horizontal exciters providing a lateral squeezing force to the table.

NOTE 1 There are situations where no table is needed in a multi-axial vibration system and specimens or fixtures are linked directly with connectors or exciters. For example, in Figure 1, no table is used and the connector is connected with the fixture.

NOTE 2 There are situations where exciters are installed inside the table as the table has a hollow structure with the outer faces functioning as mounting interfaces.

**Table 2 — Example of typical table parameters for multi-axial vibration test systems**

| **Surface dimension**<br>length (mm) × width (mm) | **Mass**<br>kg | **Maximum frequency**[1]<br>$f_{max}$<br>Hz |
|---|---|---|
| 500 × 500 | 30 | 1 000 |
| 600 × 600 | 60 | 800 |
| 800 × 800 | 120 | 500 |
| 1 000 × 1 000 | 200 | 400 |
| 1 200 × 1 200 | 300 | 300 |
| 1 500 × 1 500 | 500 | 250 |
| 2 000 × 2 000 | 1 000 | 150 |
| 3 000 × 3 000 | 4 300 | 100 |

NOTE 1 The values listed in the table are general estimations and given as an example. Consult manufacturers for specific parameters.

NOTE 2 The values listed in the table are given when using magnesium as the material of the table because magnesium is dominant in making key moving structures due to its high stiffness and low density. Other materials can be employed in manufacturing the table such as aluminium; the mass and resonant frequencies should be calculated accordingly.

NOTE 3 Height of the table is not given in the table because it is heavily associated with the design of the table depending on connector type, dimensions and other factors.

## 6.3 Connectors

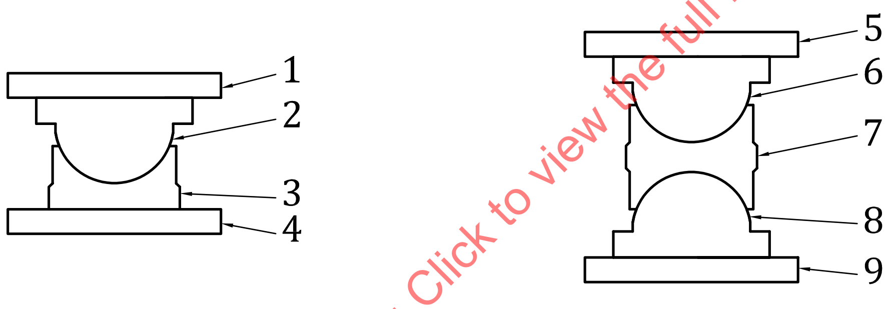
### 6.3.1 General

As the driving motion of each exciter differs in amplitude, phase or direction, rigid connections between the exciters and the table would result in a solid assembly with the exciters and table incapable of moving in any direction at all. Connectors are the mechanical device used to connect the table and the exciters, flexible in certain directions in order to decouple the motion between the exciters. Normally one connector brings in 2 degrees to 5 degrees of freedom to the system.

Connectors mainly include the following types.

### 6.3.2 Spherical connector

Spherical connectors can have one or two spheres. One single sphere connector has one spherical joint (shown in Figure 7 a), providing 3 DOFs of rotation and incapable of moving in the translational direction. Plate A and plate B in Figure 7 are connecting interfaces used to couple the two objects in relative motion, such as exciter and table. For single sphere connectors, the spherical joint is connected rigidly with Plate A and the coupling joint is connected rigidly with Plate B. A double sphere connector has two spherical joints (shown in Figure 7 b), providing 3 DOFs of rotation and 2 DOFs of translational motion, which is a good choice for decoupling multi-axial motion conflicts. The sphere connection between the spherical joint and the coupling joint creates 3 DOFs of rotation at the connection surface by preloading and lubricating the interaction surface.




**a) Single sphere connector** **b) Double sphere connector**

**Key**

1 plate A
2 spherical joint
3 coupling joint
4 plate B

5 plate A
6 the 1st spherical joint
7 coupling joint
8 the 2nd spherical joint
9 plate B

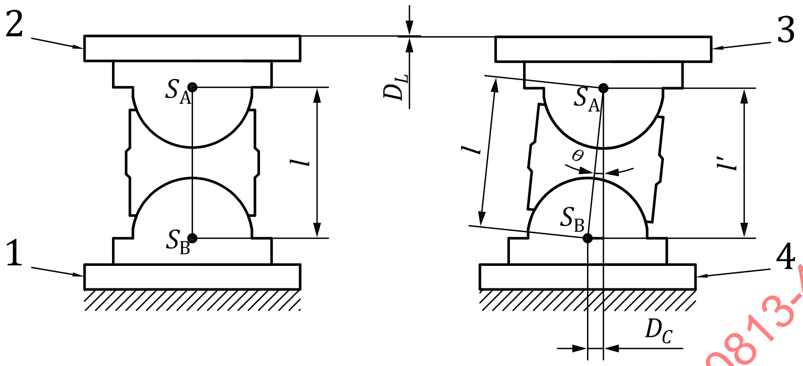
**Figure 7 — Typical designs of a spherical connector**[6]



NOTE Single sphere connectors can serve as the decoupling component in such a way that they are connected to each end of an actuator, i.e. servo-hydraulic actuator. This usage has the same decoupling utility as double sphere connectors. In this document, the use of double sphere connectors can be replaced by the use of two linked single sphere connectors.

Classified by lubrication methods, there are normally mechanical spherical connectors and hydrostatic spherical connectors used for multi-axial test systems. Mechanical spherical connectors have simpler structures, but the friction force is relatively higher causing a high force loss and high transverse motion in the table performance. Hydrostatic spherical connectors, having the quality of low friction and high frequency transmissibility, are used widely in decouple multi-axial vibration motion.

Double sphere connectors have transverse motion capabilities as illustrated in Figure 8. Plates A and B have relative motion in a transverse direction relative to the exciter axis. In Figure 8, it can be seen that when the spheres rotate by an angle $\theta$, the transverse displacement of the connector is $D_C = l \cdot \sin\theta$. The connector gets shorter in the vertical direction by $D_L = l \cdot (1 - \cos\theta)$. This indicates that when selecting double sphere connectors, the displacement of the exciters is not equal to the displacement of the table in one particular axis with the difference being $D_L$. When $\theta$ is small, $D_L$ could be neglected in practice.




**Key**

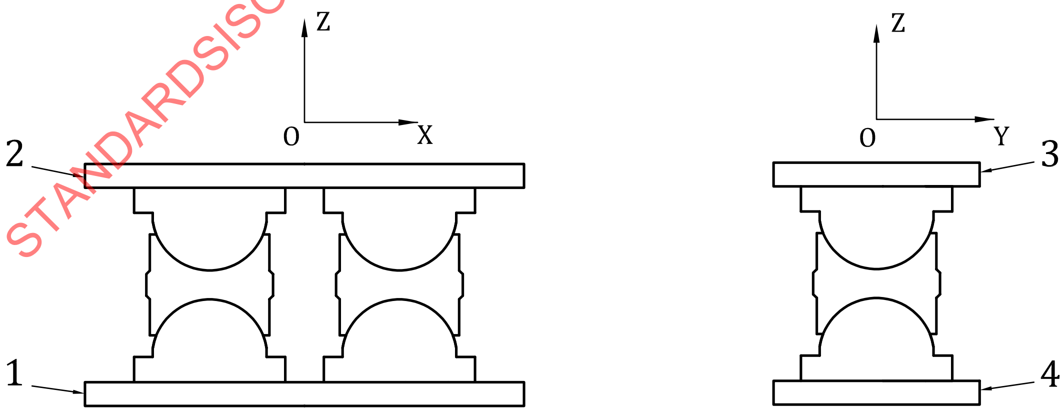
1, 4 plate A

2, 3 plate B

**Figure 8 — Transverse displacement of double sphere connectors**

Spherical connectors are also used in combination to restrain a certain degree of freedom. In Figures 9 and 10, an example of a dual spherical connector combination configuration is given to illustrate the rationale of DOF calculations. The combination of two spherical connectors restrains one rotational DOF as illustrated. Translational motion along the X and Y axes, and rotational motion about the X and Z axes are free in this configuration, DOF = 2 (linear) + 2 (angular) = 4. Likewise, a configuration of three spherical connectors restrains another rotational axis, resulting in a free motion mode with translational motion along the X and Y axes, and rotation about the Z axis, DOF = 2 (linear) + 1 (angular) = 3. Figure 10 demonstrates X axis motion in a dual sphere connector combination configuration.

An example of specification for spherical connectors is given in Table 3. Such data can be used during the selection procedure (see A.2.5). However different manufacturers provide different products with variant parameters. Consult manufacturers for specific connector parameters.




a) **Front view**

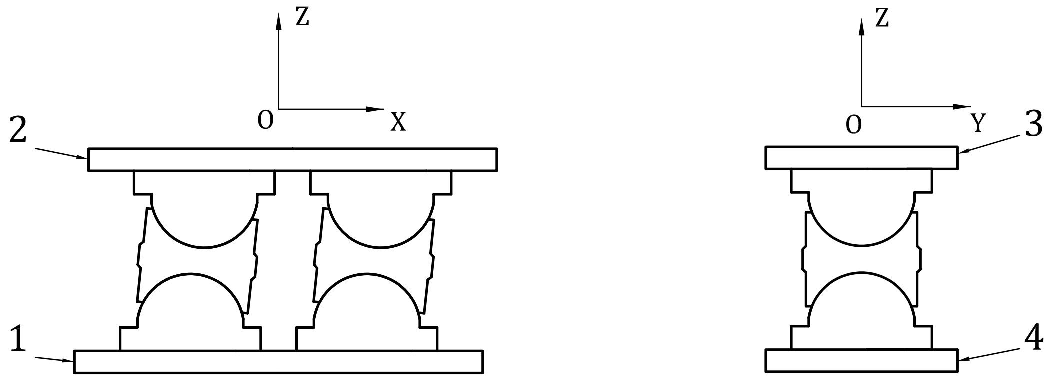
b) **Side view**

**Key**

1, 4 plate A

2, 3 plate B

**Figure 9 — Dual spherical connector combination configuration (static)**




**a) Front view** **b) Side view**

**Key**

1, 4 plate A

2, 3 plate B

NOTE Rotation about the Y axis is restrained due to two spherical connector configuration.

**Figure 10 — Dual spherical connector combination configuration (translational motion position)**

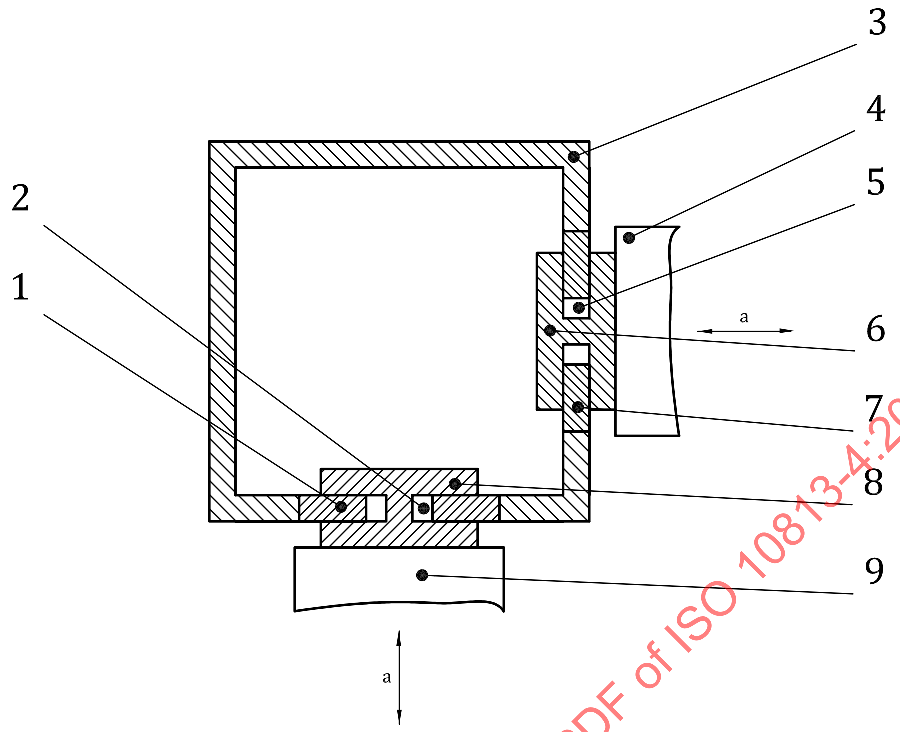
**Table 3 — Example of typical parameters of spherical connectors[6]**

| Maximum sine force<br>kN | Maximum random force<br>kN | Mass of connectors<br>kg |
|---|---|---|
| 30 | 15 | 15 |
| 60 | 30 | 25 |
| 120 | 60 | 80 |
| 180 | 90 | 450 |

### 6.3.3 Planar connector

Planar connectors enable planar motion between the sliding plate and the fixed plate. Figure 11 illustrates an example of constructing a bi-axial vibration system with planar connectors. Two exciters are configured in orthogonal directions and connected with the table using planar connectors. The sliding plate is connected rigidly with the table and the fixed plate is connected with the moving element of the exciters. Two sliding planes are formed as the sliding plate is hydrostatically lubricated and clamped by the opposing contact surfaces of the fixed plate. The sliding motion of the sliding plate and the fixed plate enables relative motion between the exciter and the table.

The displacement along each axis is restrained by the size of the motion gap between the sliding plate and the fixed plate.




**Key**

| | |
|---|---|
| 1 | sliding plate of planar connector 1 |
| 2, 5 | motion gap |
| 3 | table |
| 4 | exciter 2 |
| 6 | fixed plate of planar connector 2 |
| 7 | sliding plate of planar connector 2 |
| 8 | fixed plate of planar connector 1 |
| 9 | exciter 1 |
| a | Direction of excitation. |

**Figure 11 — Top view of a bi-axial system composed of planar connectors**[7]



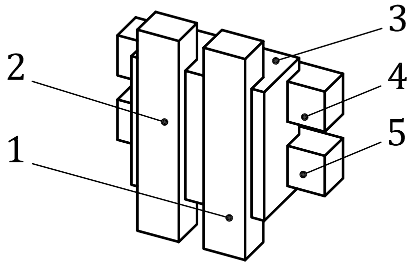
As a result of the planar restriction, each planar connector provides a 2-DOF translational motion and 1-DOF rotational motion. For example, in Figure 11 due to the circular gap between the sliding plate and the fixed plate, 2 DOFs of translational motion can be realized within the area of the gap. Using the coordinates in Figure 6, the planar connector mounted on exciter 1 restrains the rotation of the table about the Y and Z axes and the connector mounted on exciter 2 restrains the rotation of the table about the X and Z axes. Therefore, all rotational DOFs of the table have been restrained. With appropriate combinations of planar connectors, bi-axial or tri-axial translational vibration systems can be constructed.

### 6.3.4 Orthogonal linear bearing set

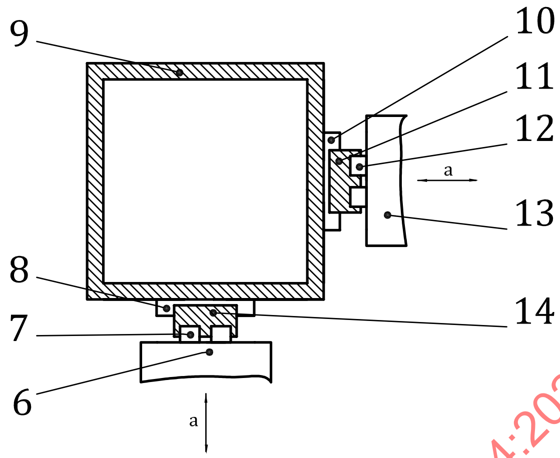
Orthogonally arranged linear bearing sets function similarly to planar connectors, providing 2-DOF translational motion but no rotations. They can be used to construct a bi-axial or tri-axial vibration test system as planar connectors do.

As shown in Figure 12 a), an orthogonal linear bearing set is composed of perpendicularly arranged linear bearings. The vertical and horizontal guide rails slide in the rail housing, enabling 2-DOF planar motion like a planar connector. The vertical and horizontal guide rails are connected with the moving elements of the exciter and the table respectively. Thus the relative motions of the table and the exciters are achieved.




**a) Orthogonal linear bearing set**




**b) Top view of bi-axial system**

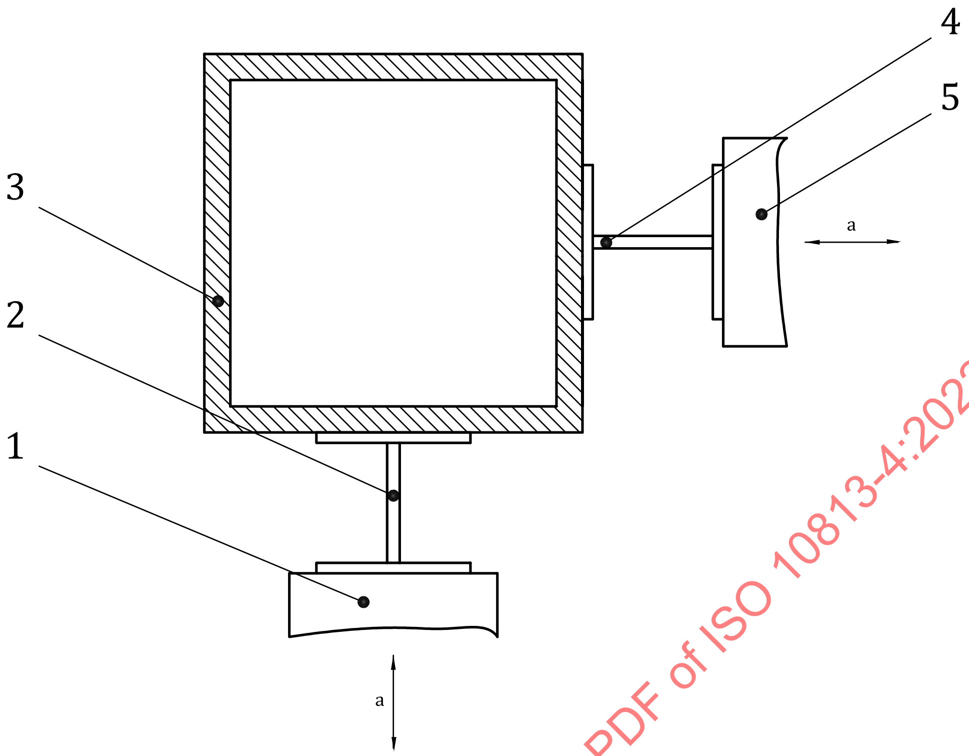
**Key**

| | | | |
|---|---|---|---|
| 1, 2, 7, 12 | vertical guide rail | 6 | exciter 1 |
| 3, 11, 14 | rail housing | 9 | table |
| 4, 5, 8, 10 | horizontal guide rail | 13 | exciter 2 |
| | | a | Direction of excitation. |

**Figure 12 — Bi-axial system composed of orthogonal linear bearing sets**

### 6.3.5 Drive rod

A drive rod, also known as a stinger, is a flexible rod with a large length-diameter ratio, used in multi-axial vibration testing where vibratory force and displacement are relatively small. Figure 13 shows an example of a bi-axial system composed of drive rods. The rod is relatively rigid in the longitudinal direction and flexible in the cross-axial direction. Vibration can be transmitted to the table by the stiffness of the rod in the axial direction while cross-axial motion is decoupled by bending or torsional deformation of the rod.




**Key**

1 exciter 1

2 drive rod 1

3 table

4 drive rod 2

5 exciter 2

a Direction of excitation.

**Figure 13 — Top view of a bi-axial system composed of drive rods**

### 6.3.6 Other connectors

Spherical connectors and planar connectors are the most common solutions for multi-axial vibration systems and therefore this document mainly deals with the selection of the above two kinds.

Other connectors exist in practice. Consult the manufacturers for more information on connectors.

For example, there are also connectors composed of a sphere joint and a planar restriction, providing 5-DOF motion, the same as a double sphere connector. This kind of connector can be an alternative to double sphere connectors.

For servo-hydraulic vibration systems, mechanical joints with 1-DOF, 2-DOF or 3-DOF of rotation are also used.

## 6.4 Other components

Other components in a multi-axial test system may include power amplifiers, hydraulic power supplies, servo valves, cooling facilities, vibration controllers, vibration transducers and seismic foundations etc.

See ISO 10813-1 for the selection of power amplifiers for electrodynamic vibration generators and hydraulic power supplies for servo-hydraulic vibration generators.

Cooling facilities, normally air-cooling or water-cooling facilities, must provide sufficient cooling capability for consuming the heat generated during vibration testing.

MIMO (multiple input multiple output) controllers may be selected according to the number of axes needed for a test.

Tri-axial vibration transducers or orthogonally aligned single axis transducers can be placed on the control/monitor position as determined by the test purpose.

Normally air springs are placed between vibration equipment and the ground to isolate or absorb any vibration that would be transmitted to the ground. This approach is useful when the mass of the specimen is relatively small compared with the mass of the vibration generating system. For a test system with a heavy specimen, this approach may result in a high level of equipment vibration and therefore a seismic foundation is required. The weight of the seismic foundation is suggested to be no less than 10 to 20 times of the maximum force in a multi-axial system. When no air springs are placed between the vibration generating system and the ground, the higher value should be selected. For example, the foundation mass for a tri-axial system is suggested to be $20\left(F_X{}^2+F_Y{}^2+F_Z{}^2\right)^{1/2}/g_n$, where $F_X$, $F_Y$ and $F_Z$ are maximum forces in each axis.

NOTE The interlock function between components in a multi-axial system should be employed, meaning the running status of different components are monitored and managed in an integrated control board enabling system shutdown when an abnormality is detected in one component.

## 7 System parameters

### 7.1 General

Aside from the basic parameters of individual exciters constituting the multi-axial system, specific parameters for multi-axial test systems are given below. The parameters can be used to describe the capability and characteristics of multi-axial systems, and also are important factors to be considered during selection of multi-axial systems.

### 7.2 Number of exciters

This is the total number of exciters, $N_e$, used in the multi-axial test system. It is important in kinematics analysis of the parallel mechanism. When the number of exciters is greater than the number of total DOFs of the system, it is an over-actuated system, meaning some exciters need to be controlled in phase to exorcise the impacts of the over actuation. Also, if the number of exciters is less than the number of total DOFs, it is an under-actuated system; some specified motions of the table cannot be achieved.

### 7.3 Number of total, linear and angular degrees of freedom

The number of total DOFs, $N_t$, is the number of degree of freedoms the table has in total, including linear motion and angular motion. It is an important parameter of the multi-axial test system describing the most basic motion capabilities. The number of linear DOFs, $N_l$, is the number of degrees of freedom that permit linear motion; the number of angular DOFs, $N_a$, is the number of degrees of freedom that permit angular motion. The number of total DOFs is calculated as the sum of the number of linear DOFs and the number of angular DOFs by Formula (1):

$$N_t = N_l + N_a \quad (1)$$

According to mechanism and machine theory[8], the number of total DOFs can be calculated by Formula (2):

$$N_t = 6N_m - \sum_{i=1}^{5} i\,N_i \quad (2)$$

where,

$N_m$ is the number of moving elements in the kinematic system;

$i$ is the number of DOFs that have been restrained by a certain kinematic pair;

$N_i$ is the number of the kinematic pairs that have $i$ restraints.

EXAMPLE Taking configuration C7 from Table 1, the number of moving elements, $N_m$, in the kinematic system is 7, including 6 armatures and 1 table. There are 6 double sphere connectors, each having 1 restraint so $N_1$ = 6. The armature of each of the 6 exciters has 5 restraints, so $N_5$ = 6. Thus the number of total DOF is determined by the following formula:

$$N_t = 6N_m - 1N_1 - 5N_5 = 6 \times 7 - 1 \times 6 - 5 \times 6 = 6\,.$$

## 7.4 Maximum displacement

For each axis, the maximum displacement is the maximum displacement of the table along the concerning vector direction.

The system maximum displacement provided by the manufacturer should be smaller than the maximum displacement of the exciters in the same direction given some safety tolerance. Also, transverse motion of each connector, i.e. the motion in the plane perpendicular to the direction of excitation provided with a connector, needs to be checked to be within designated limits, if relevant.

NOTE The axial displacement of the table can be equal to the displacement of the exciter in that direction or not, depending on connector characteristics.

## 7.5 Maximum velocity

For each axis, the maximum velocity is the maximum velocity of the table along the concerning vector direction.

NOTE The axial velocity of the table can be equal to the velocity of the exciter in that direction or not, depending on connector characteristics.

## 7.6 Maximum acceleration

For each axis, the maximum acceleration is the maximum acceleration on the bare table without payloads, including sine acceleration and random acceleration (r.m.s. value).

NOTE The axial acceleration of the table can be equal to the acceleration of the exciter in that direction or not, depending on connector characteristics.

## 7.7 Maximum angular displacement

For each axis, the maximum angular displacement is the maximum angular displacement of the table about the concerning vector direction.

The relationship between rotation and linear excitation motion can be interpreted through Figure 14. A beam labelled AB with a length of $l$ rotates about its centre by an angle $\theta$. After rotation, the beam position is A'B'. $D_B$ is the linear motion of point B. The geometric relationship between the quantities is given by Formula (3):

$$\sin\theta = \frac{D_B}{l/2} \qquad (3)$$

In practice, when $\theta$ is relatively small, it equals to sin $\theta$ as an assumption and can be calculated by Formula (4):

$$\theta = \frac{D_B}{l/2} \qquad (4)$$

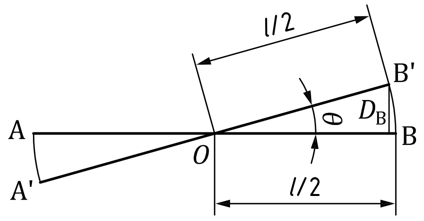



**Figure 14 — Illustration of angular motion**

When the rotation is driven by a pair of exciters applied at points A and B in directions perpendicular to beam AB, the angular displacement is given by Formula (5):

$$\theta = \frac{\Delta D}{l} \tag{5}$$

where

$\Delta D$ is the difference between linear displacements generated by the exciters, in metres;

$\theta$ is the angular displacement generated by the pair of exciters, in radians;

$l$ is the distance between the excitation points, in metres.

There are situations where the rotation is produced by a single exciter with proper suspension structures. In this case, Formula (5) still stands with $\Delta D$ being the displacement generated by the exciter and $l$ being the distance between the exciter and the rotation centre.

## 7.8 Maximum angular velocity

For each axis, the maximum angular velocity is the maximum angular velocity of the table about the concerning vector direction.

By differentiating Formula (5), the angular velocity can be calculated through a given linear velocity by Formula (6):

$$\omega = \frac{\Delta v}{l} \tag{6}$$

where

$\Delta v$ is the linear velocity difference between the two exciters which provide angular vibration, in metres per second;

$\omega$ is the angular velocity generated by the two exciters, in radians per second;

$l$ is the distance between the centres of the two exciters, in metres.

In the case of rotation produced by a single exciter with a proper suspension structure, Formula (6) still stands with $\Delta v$ being the velocity of the exciter and $l$ being the distance between the exciter and the rotation centre.

## 7.9 Maximum angular acceleration

For each axis, the maximum angular acceleration is the maximum angular acceleration of the table about the concerning vector direction.



After differentiating Formula (6), the angular acceleration is given by Formula (7):

$$\alpha = \frac{\Delta a}{l} \tag{7}$$

where

$\Delta a$ is the linear acceleration difference between the two exciters providing angular vibration, in metres per second squared;

$\alpha$ is the angular acceleration generated by the two exciters, in radians per second squared;

$l$ is the distance between the centres of the two exciters, in metres.

In the case of rotation produced by a single exciter with a proper suspension structure, Formula (7) still stands with $\Delta a$ being the acceleration of the exciter and $l$ being the distance between the exciter and the rotation centre.

## 7.10 Frequency range

The frequency range is the range of frequencies within which the specified parameters apply.

The frequency range is limited by the resonance frequencies of all components constituting the moving system. Therefore it is ideal that the resonance frequencies of the components be outside the required testing frequency range.

For electrodynamic vibration generators, the frequency range is highly dependent on the first resonance frequency of the table. The lower frequency limit depends on the vibration generator isolation system. For an air spring isolated body, the lower frequency limit is normally 5 Hz, whereas for a rigid mounting exciter the lower frequency limit can reach down to 2 Hz.

The upper frequency limit is generally a disadvantage of servo-hydraulic vibration generators, normally less than 200 Hz, but the lower limit is down to DC which outperforms electrodynamic vibration generators.

## 7.11 Parasitic motion

### 7.11.1 General

A multi-exciter system forces every point of the table or specimen, assumed to be a rigid body, to move along a specific, sometimes rather exotic orbit. This orbit may be either strictly determined (for example, for time-history excitation) or specified by some statistical parameters (for broad-band random excitation). However, the target orbit is actually distorted by some parasitic motion which cannot be adequately compensated by the control circuit of the system. Such a distortion can be primarily caused by one of the following effects: non-linear transfer function of the system, non-rigid table, or transverse motions of single generators that compose the system. These effects can be described by harmonic distortion, non-uniformity ratio, and transverse motion respectively.

### 7.11.2 Harmonic distortion

For translational sine excitation, non-linearity is commonly described through harmonic distortion (see ISO 15261). The parameter is used in selection of exciters according to test requirements. For those tests having stringent distortion requirements, electrodynamic vibration generators are suggested because normally servo-hydraulic vibration generators have higher levels of harmonic distortions.

Harmonic distortion is also important in assessing if the guidance system or connectors provide smooth boundary conditions for the moving table. In a multi-axis system, a poorly assembled exciter guidance system or connector can cause high distortion over the table which may bring in undesired signals to the testing specimen, which may induce over-testing.

### 7.11.3 Non-uniformity ratio

This is the value of an acceleration ratio as a function of frequency indicating the non-uniformity of the table when outputting a vibration force along three or two coordinate axes. The non-uniformity ratio is an indication of the level of excitation force being uniformly the desired value across the surface of the table or not. High levels of non-uniformity may not be accepted by the test requirements and therefore a well-suspended and high-resonant table is to be selected. The value of the non-uniformity ratio is associated directly with the numbers and types of connectors used in the multi-axial test system and also their configurations. At non-rigid-body frequencies, the non-uniformity of the table is related to the mode shapes at those resonant frequencies.

For multi-axial linear vibration test systems, the non-uniformity ratio can be calculated through the maximum absolute value of the difference between the acceleration at a point on the table and the acceleration at the reference point (point used to control the test, see IEC 60068-2-64[2]) divided by the acceleration value at the reference point by Formula (8):

$$\sigma(f) = \frac{|a_i(f) - a_0(f)|_{\max}}{a_0(f)} \times 100\% \quad (8)$$

where

$\sigma(f)$ is the non-uniformity ratio of the table at the frequency, $f$;

$a_i(f)$ is the peak acceleration value of the $i^{\text{th}}$ monitor accelerometers placed on the table surface;

$a_0(f)$ is the peak acceleration value of the control accelerometer.

NOTE 1 For single-channel control scenario, $a_0(f)$ is normally the acceleration value of the table centre; for multi-channel control scenario, $a_0(f)$ is the average value of the control channels.

NOTE 2 For each axis, there is a value of non-uniformity ratio, symbolized as $\sigma_X(f)$, $\sigma_Y(f)$, $\sigma_Z(f)$.

In order to catch the peaks of vibrations over the table at relevant resonance modes, it is suggested to include as many typical structures of the table as possible in the selection of monitor locations[8] such as orthogonal axes, diagonal axes and off-diagonal locations.



### 7.11.4 Transverse motion

#### 7.11.4.1 General

Transverse motion is undesired motion of the table in one direction brought about by controlled motion in a perpendicular direction. At non-resonant frequencies of the moving element, transverse motion is mainly caused by characteristics of connectors, suspensions and exciter guidance systems etc. When resonance of the moving element happens, transverse motion is mainly caused by resonance.

For instance, the transverse motion brought about by double sphere connectors (see Figure 8) can be assessed by Formula (9):

$$T = D_L / D_C = [l(1-\cos\theta)]/(l \sin\theta) = \tan(\theta/2) \quad (9)$$

In this document, only transverse motion in linear vibration test equipment is considered.

#### 7.11.4.2 Transverse motion ratio for bi-axial linear vibration test equipment

This value is the maximum ratio of the acceleration along the “third” axis, which is not required as a control axis in the bi-axial linear vibration test system, to the resultant acceleration of the two controlled axes. This value is usually expressed as a function of frequency. The transverse motion ratio for bi-axial linear vibration test equipment indicates the level of unwanted “third” axis motion, which may be required by the test specification and therefore is considered during selection.

#### 7.11.4.3 Transverse motion for tri-axial linear vibration testing equipment

Normally transverse motion is not concerned in a tri-axial linear vibration test system because all motions in the three axes are desired. However, when excitation levels along three axes differ considerably, an axis having relatively low vibration levels may not be controllable to the desired levels at some frequencies as a result of transverse motion brought about by perpendicular axes having high levels of vibration.

To measure the transverse motion for the above reason, a method is recommended as follows. Control one axis and leave the other axes free. Measure the uncontrolled motion in the transverse direction brought about by the motion of the controlled axis. For an electrodynamic vibration generator, the field should be switched on for all exciters. For each uncontrolled axis, the ratio between the uncontrolled level and the controlled level can be expressed as a function of frequency $\delta(f)$ by Formula (10):

$$\delta(f) = \frac{A_{uc}(f)}{A_c(f)} \times 100\% \quad (10)$$

where

$A_{uc}(f)$ is the level of vibration along the uncontrolled axis;

$A_c(f)$ is the level of vibration along the controlled axis.

The level of vibration can be expressed as power spectral density (PSD) or peak acceleration value for random and sine tests respectively.

NOTE The method proposed in this document is an initial investigation into this problem. In practice, many factors affect the controllable transverse motion levels such as profile characteristics, system resonances and controller capability. The user may consult manufacturers for solutions to specific test requirements.

### 7.12 Maximum payload

This is the maximum static mass that the table can withstand without malfunction.

### 7.13 Maximum torque

This is the limiting torque in pitch, $C_\alpha$, roll, $C_\beta$, and yaw, $C_\gamma$, due to static and dynamic forces which can be exerted on the table without damage.

### 7.14 Table suspension stiffness

Table suspension stiffness is the rigidity of the table, referring to the capability of the table at the connection points of suspension structures to resist deformation in response to applied force or torque. Table suspension decides the boundary condition of the testing system; thus, the suspension stiffness matters when certain boundary conditions, such as free or flexible, are required by test specifications.

Table suspension stiffness includes linear stiffness along three coordinate axes, $K_X$, $K_Y$, $K_Z$, in Newtons per metre, and rotational stiffness about three coordinate axes, $K_{rX}$, $K_{rY}$, $K_{rZ}$, in Newton metres per radian.

## 8 Selection procedures

### 8.1 General

Test requirements are the basis for selection of multi-axial environmental test equipment.

In selection of a multi-axial vibration system, the following procedures are recommended.

## 8.2 Determination of the exciter and connector numbers

Appropriate selection of the number and type of connectors and exciters should be made according to the DOF number and vibration type (linear or angular) of the test requirements. For example, for a test requiring a 3-DOF linear vibration, planar connectors and hydrostatic spherical connectors can be selected accordingly. The number of exciters to be selected is always at least the number of DOFs in the test requirements.

Recommended configurations of exciters and connectors are given in Table 4.

**Table 4 — Example of recommended configurations for typical multi-axial test requirements**

| Testing requirements | | | | Suggested configuration | |
|---|---|---|---|---|---|
| $N_t$ | $N_l$ | $N_a$ | Description | Conf. Code | Connector |
| 2 | 1 | 1 | Two independent excitations in vertical direction, such as missile testing. | C1 | *Option 1*: 4 spherical connectors [a] |
| | | | | | *Option 2*: 2 spherical connectors [a] |
| 2 | 2 | 0 | Two-axial excitation in orthogonal direction. | C4/C5 | *Option 1*: 2 planar connectors |
| | | | | | *Option 2*: 2 spherical connectors [a] |
| | | | | | *Option 3*: 5 spherical connectors [a] |
| 3 | 3 | 0 | Tri-axial excitation in Cartesian coordinates. | C6 | *Option 1:* 6 spherical connectors |
| | | | | | *Option 2:* 3 planar connectors |
| | | | | | *Option 3:* 3 spherical connectors [a] |
| 3 | 1 | 2 | Four exciter independent excitation in vertical direction. | C3 | 4 spherical connectors [a] |
| 6 | 3 | 3 | 6-DOF excitation. | C7 | 6 spherical connectors |
| | | | | C10 | 8 spherical connectors |
| | | | | C12 | 12 spherical connectors |

**Key**

$N_t$: Number of total DOFs.

$N_l$: Number of linear DOFs.

$N_a$: Number of angular DOFs.

[a] This structure is not fully determined. Additional suspension apparatus will be needed to stabilize the table and specimen. The suspension device should suspend the table and specimen at the centre of the balanced position and be flexible enough to travel along desired vibration directions.

NOTE The suggested configurations are not the only possible or best solutions for each test requirement. Consult the manufacturers for other possible solutions.



## 8.3 Determination of exciter types

### 8.3.1 General

The following factors should be considered to select or eliminate a certain kind of exciter according to the characteristics of different vibration generators.

### 8.3.2 Test waveform

The required waveform is considered whether it is sinusoidal at a fixed frequency, sinusoidal sweep, random or time history. Appropriate types of exciters can be selected for the required test waveforms.

Refer to ISO 10813-1 for detailed selection procedures of exciters according to test waveforms.

### 8.3.3 Frequency range

Appropriate types of exciters can be selected according to the required frequency range.

Refer to ISO 10813-1 for detailed selection procedures of exciters according to frequency range.

### 8.3.4 Maximum displacement, velocity, and acceleration

Appropriate types of exciters can be selected according to the maximum displacement, velocity, and acceleration requirements.

For angular vibration test requirements, linear displacement, velocity, and acceleration of the exciters can roughly be calculated from the given angular displacement, velocity, and acceleration values following 7.7, 7.8 and 7.9. In this way, angular vibration requirements can be transformed into linear vibration requirements and vibration generators can be selected accordingly.

Refer to ISO 10813-1 for detailed selection procedures of exciters according to maximum displacement, velocity, and acceleration.

### 8.3.5 Maximum force

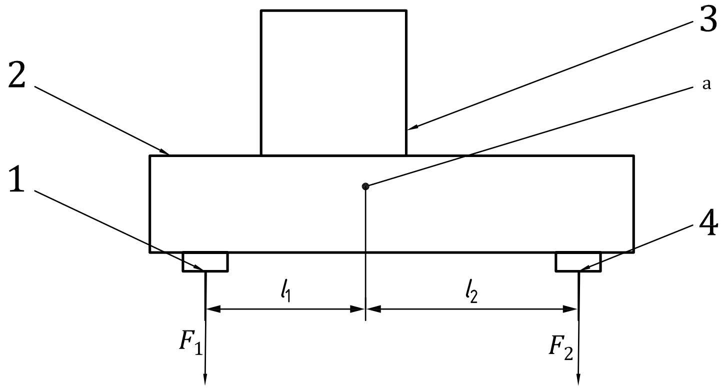
Appropriate types of exciters can be selected according to maximum force requirements.

The linear and angular acceleration of the moving element are generated by the forces of related exciters. An example of two exciters in one axis providing linear and angular vibration is given in Figure 15. The forces can be calculated by Formula (11)[9]:

$$\begin{cases} \sum F_i = ma \\ \sum F_i l_i = I\alpha \end{cases} \quad (11)$$

where

- $F_i$ is the force of the $i^{\text{th}}$ exciter in the axis under consideration;
- $l_i$ is the distance between the $i^{\text{th}}$ exciter to the centre of gravity of the table and specimen assembly;
- $m$ is the mass of the table and specimen assembly;
- $a$ is the linear acceleration at the centre of gravity of the table and specimen assembly;
- $\alpha$ is the angular acceleration about the centre of gravity of the table and specimen assembly;
- $I$ is the moment of inertia about the centre of gravity of the table and specimen assembly.




**Key**

1, 4 excitation point

2 table

3 specimen

[a] Centre of gravity of the specimen and table assembly.

**Figure 15 — Force calculation example of two exciters**

NOTE The moment of inertia is achieved through calculation based on the physical and geometric characteristics of the specimen, fixture, and the table.

Based on the above calculation, the requirements for each exciter can be determined. Appropriate selection of the model of exciters and connectors can be obtained. It is always suggested that the selected exciters have rated force, acceleration, velocity, and displacement capabilities which are no less than 1,2 to 1,5 times what is required by the test. After exciters are selected for each axis, the masses of their moving elements are included in the respective *m*.

### 8.3.6 Validation of the proposed selection

When the models of the exciters and connectors and all the configurations have been determined, calculate the maximum system performance to validate the capability to conduct the test as required.

NOTE Always validate the maximum displacement and load of the test with the capability of the selected configuration to ensure test safety.

### 8.3.7 Other factors to be considered

When dealing with test requirements having demands which are not mentioned in the above procedures, such as parasitic motion, torque capacity or suspension stiffness, those factors need to be considered particularly during selection.



# Annex A
(informative)

# Examples of selections

## A.1 General

The process of determining system requirements can be simplified into a mechanistic approach. However, there are many considerations that have to be made which can only come from experience and detailed knowledge of the subject.

The examples below consider that the device under test is symmetrical and a true mass, which may not be possible in practice. For these examples, only the basic system parameters are considered. Such parameters as load support capability, suspension stiffness and isolation system resonance are not considered as it would make the example too complex.

The selection of standard electrodynamic vibration generators and servo-hydraulic vibration generators are based on data given in ISO 10813-1:2004, Tables 1 and 2.

The definitions of the symbols used in this document can be found in Table A.1.

**Table A.1 — Symbols used in Annex A**

| | |
|---|---|
| $m_s$ | Mass of the specimen (including fixtures) |
| $m_t$ | Mass of the table |
| $m_e$ | Mass of the moving element of the exciter |
| $m_c$ | Mass of the moving element of the connector |
| $a_X$ | Acceleration along the X axis |
| $a_Y$ | Acceleration along the Y axis |
| $a_Z$ | Acceleration along the Z axis |
| $F_X$ | Vibration force in the X axis |
| $F_Y$ | Vibration force in the Y axis |
| $F_Z$ | Vibration force in the Z axis |
| $F_e$ | Vibration force of exciters |
| $F_c$ | Vibration force of connectors |
| $\alpha_X$ | Angular acceleration about the X axis |
| $\alpha_Y$ | Angular acceleration about the Y axis |
| $\alpha_Z$ | Angular acceleration about the Z axis |
| NOTE The combination usage of symbols can be found in the calculation process, which can be interpreted as both meanings of subscripts. | |

## A.2 Example 1: Selection of a tri-axial linear test system

### A.2.1 Test conditions

The test conditions are specified in Table A.2.