

INTERNATIONAL STANDARD

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**Semiconductor devices – Discrete devices –
Part 14-4: Semiconductor accelerometers**

**Dispositifs à semiconducteurs – Dispositifs discrets –
Partie 14-4: Accéléromètres à semiconducteurs**



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**Semiconductor devices – Discrete devices –
Part 14-4: Semiconductor accelerometers**

**Dispositifs à semiconducteurs – Dispositifs discrets –
Partie 14-4: Accéléromètres à semiconducteurs**

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**SEMICONDUCTOR DEVICES –
DISCRETE DEVICES –****Part 14-4: Semiconductor accelerometers**

FOREWORD

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International Standard IEC 60747-14-4 has been prepared by subcommittee 47E: Discrete semiconductor devices, of IEC technical committee 47: Semiconductor devices.

This part of IEC 60747 should be read in conjunction with IEC 60747-1:2006. It provides basic information on semiconductor

- terminology;
- letter symbols;
- essential ratings and characteristics;
- measuring methods;
- acceptance and reliability.

The text of this standard is based on the following documents:

FDIS	Report on voting
47E/405/FDIS	47E/409/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 60747 series, under the general title *Semiconductor devices – Discrete devices*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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INTRODUCTION

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning following items.

- a) Measurement technique and apparatus for matrix sensitivity in “definition of sensitivity matrix of an accelerometer” given in Subclause 4.1.5 and Annex A.
- b) Measurement technique and apparatus for the dynamic linearity measurement of AC accelerometers in “dynamic linearity measurement using an impact acceleration generator” given in Annex B.
- c) Measurement technique and apparatus for the frequency response measurement of accelerometers under the frequency bandwidth control in “method of controlling the frequency bandwidth of the shock acceleration” given in Clause C.5.
- d) Measurement technique and apparatus for the dynamic response and peak sensitivity measurement of accelerometers in the form of matrix using elastic pulse in “definition of sensitivity matrix of an accelerometer” given in Annex A.
- e) Projectiles for frequency bandwidth control in “method of controlling the frequency bandwidth of the shock acceleration” given in Clause C.5 and for the dynamic response and peak sensitivity measurement of accelerometers in the form of matrix using elastic pulse in “definition of sensitivity matrix of an accelerometer” given in Annex A.

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SEMICONDUCTOR DEVICES – DISCRETE DEVICES –

Part 14-4: Semiconductor accelerometers

1 Scope

This part of IEC 60747 applies to semiconductor accelerometers for all types of products.

This standard applies not only to typical semiconductor accelerometers with built-in electric circuits, but also to semiconductor accelerometers accompanied by external circuits.

This standard does not (or should not) violate (or interfere with) the agreement between customers and suppliers in terms of a new model or parameters for business.

NOTE 1 This standard, although directed toward semiconductor accelerometers, may be applied in whole or in part to any mass produced type of accelerometer.

NOTE 2 The purpose of this standard is to allow for a systematic description, which covers the subjects initiated by the advent of semiconductor accelerometers. The tasks imposed on the semiconductor accelerometers are not only common to all accelerometers but also inherent to them and not yet totally solved. The descriptions are based on latest research results. One typical example is the multi-axis accelerometer. This standard states the method of measuring acceleration as a vector quantity using multi-axis accelerometers.

NOTE 3 This standard does not conflict in any way with any existing parts of either ISO 16063 or ISO 5347. This standard intends to provide the concepts and the procedures of calibration of the semiconductor multi-axis accelerometers which are used not only for the measurement of acceleration but also for the control of motion in the wide frequencies ranging from DC.

2 Normative references

The following referenced documents are indispensable for the application 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.

IEC 60747-1:2006, *Semiconductor devices – Part 1:General*

IEC 60749 (all parts), *Semiconductor devices – Mechanical and climate test methods*

IEC 60749-1, *Semiconductor devices – Mechanical and climate test methods – Part 1: General*

IEC 60749-5, *Semiconductor devices – Mechanical and climatic test methods – Part 5: Steady-state temperature humidity bias life test*

IEC 60749-6, *Semiconductor devices – Mechanical and climatic test methods – Part 6: Storage at high temperature*

IEC 60749-10, *Semiconductor devices – Mechanical and climatic test methods – Part 10: Mechanical shock*

IEC 60749-11, *Semiconductor devices – Mechanical and climatic test methods – Part 11: Rapid change of temperature – Two-fluid-bath method*

IEC 60749-12, *Semiconductor devices – Mechanical and climatic test methods – Part 12: Vibration, variable frequency*

IEC 60749-13, *Semiconductor devices – Mechanical and climatic test methods – Part 13: Salt atmosphere*

IEC 60749-25, *Semiconductor devices – Mechanical and climatic test methods – Part 25: Temperature cycling*

IEC 61000-4 (all parts), *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques*

IEC 61000-4-2:1995, *Electromagnetic compatibility (EMC) – Part 4-2: Testing and measurement techniques – Electrostatic discharge immunity test*

IEC 61000-4-3:2006, *Electromagnetic compatibility (EMC) – Part 4-3: Testing and measurement techniques – Radiated, radio-frequency, electromagnetic field immunity test*

IEC 61000-4-4:2004, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 4: Electrical fast transient/burst immunity test*

ISO 5347 (all parts), *Methods for the calibration of vibration and shock pick-ups*

ISO 5347-11:1993, *Methods for the calibration of vibration and shock pick-ups – Part 11: Testing of transverse vibration sensitivity*

ISO/IEC Guide 99, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

3 Terminology and letter symbols

3.1 Terms and definitions

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

3.1.1

accelerometer

device whose output is a vector representing the projection of the acceleration in a multidimensional space of the acceleration applied to it

3.1.2

AC accelerometer

accelerometer which has a high-pass filter in either real or equivalent signal processing circuits in characteristics

NOTE It responds to AC band domain input in its frequency characteristics. This type of accelerometer is useful for measurement of vibration, shock and sway.

3.1.3

DC accelerometer

accelerometer that responds to the input from DC to specified AC band domain in its frequency characteristics

NOTE It has the second order open-loop system or closed-loop system. This type of accelerometer is useful for measurement of inclination angle, velocity and displacement by integration of output.

3.1.4

semiconductor accelerometer

accelerometer manufactured by the semiconductor technology for at least one acceleration sensing element

NOTE A typical example might be a combination of a silicon seismic system by micro-machining with sensing mechanism and an electrical circuit.

3.1.5

one-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension one

3.1.6

two-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension two

3.1.7

three-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension three

3.1.8

four-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension four

3.1.9

five-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension five

3.1.10

six-dimensional accelerometer

accelerometer whose characteristics are measured in the calibration acceleration vector space with dimension six

3.1.11

level 1 accelerometer

accelerometer with a sensitivity that is not defined in a form of a matrix

NOTE The sensitivity along the input axis is separated from the cross axis sensitivity.

3.1.12

level 2 accelerometer

accelerometer with sensitivity in the form of a matrix in which all components of the matrix are constant as a function of frequency and other parameters if necessary

3.1.13

level 3 accelerometer

accelerometer with sensitivity in the form of a matrix in which some of the components are defined as functions of frequency and other parameters if necessary

3.1.14

level 4 accelerometer

accelerometer with sensitivity in the form of a matrix in which all of the components are defined as functions of frequency and other parameters if necessary

3.1.15**input acceleration vector space**

real motion vector space where the input acceleration is an element of a set

NOTE Input acceleration vector space is divided into the application acceleration vector space and the calibration acceleration vector space.

3.1.16**accelerometer output vector space**

vector space where the output signal from an accelerometer is an element of a set

3.1.17**gravitational acceleration**

acceleration due to gravity

NOTE The symbol g denotes a unit of acceleration equal in magnitude to the value of local gravity and the symbol g_n represents the standard value of g under international agreement, $g_n=9,80665 \text{ m/s}^2$.

3.1.18**input axis**

axis along or about which the accelerometer output for the applied acceleration indicates a maximum value

NOTE Neither misalignment nor cross-axis sensitivity compensation is employed. The IA direction only may be marked on the external package.

3.1.19**input reference axis**

direction of an axis that is nominally parallel to the input axis

NOTE It is defined by the package mounting surfaces or external package markings.

3.1.20**output axis**

axis along or about which the output of the accelerometer is measured

NOTE In some cases, it is referred to as the hinge or flexure axis.

3.1.21**output reference axis**

direction of an axis that is nominally parallel to the output axis

NOTE It is defined by the package mounting surfaces or external package markings.

3.1.22**pendulum axis**

axis through the proof mass centre in pendulum accelerometers

NOTE It is perpendicular to and intersecting the output axis.

3.1.23**pendulum reference axis**

direction of an axis that is nominally parallel to the pendulum axis

NOTE It is defined by the package mounting surfaces or external package markings.

3.1.24**misalignment**

angle between an input axis and the corresponding input reference axis that is indicated on the accelerometer package, when the device is at a 0 g position

3.1.25

pick-off

device that indicates the displacement of proof mass generated by input acceleration

3.1.26

proof mass

mass whose inertia produces an acceleration signal

NOTE Pendulum-mass or translational-mass is generally used.

3.1.27

bias

outputs without any acceleration along the input axis

NOTE It may be represented by the algebraic means between the peak outputs given when acceleration is applied equally along both directions of the input axis.

3.1.28

bias discrepancy

difference between the bias values at the 1 g and the 0 g positions

NOTE It is a function of the non-linear characteristics of sensitivity.

3.1.29

bias error

algebraic difference between the bias of a device and the nominal bias in the specification

NOTE The bias specification of the device is comprised of the variation due to temperature and voltage.

3.1.30

temperature coefficient of bias

change in bias per unit change in temperature relative to the bias at the specified temperature

3.1.31

ratiometricity

proportionality of the output acceleration to the supply voltage change on the accelerometer

3.1.32

supply voltage range

maximum and minimum supply voltage values among which the device can operate normally

3.1.33

measurement range

maximum and minimum acceleration values that are measurable

3.1.34

input acceleration limits

extreme values of the input acceleration, within which the accelerometer can keep the specified performance

3.1.35

first resonant frequency

lowest frequency at which the ratio of output versus input acceleration takes a peak value

3.1.36

dynamic linearity

linearity that is concerned with the relationship between the transient input signals and output signals

NOTE See Annex B.

3.1.37**sensitivity matrix**

matrix that transforms the input acceleration vector space to the output signal vector space under the assumption that the transformation is linear

NOTE 1 Diagonal terms and non-diagonal terms correspond to normal sensitivities and cross-sensitivities, respectively.

NOTE 2 Calibration of an accelerometer should be recognized as the process of determining all of the components of the sensitivity matrix.

NOTE 3 Matrix sensitivity can be used to describe the sensitivity of accelerometers of level 2, 3 and 4. It is used to place an emphasis on the difference between the conventional sensitivity of the level 1 and level 2, 3 and 4 accelerometers (see 4.1.5: Classification)

3.1.38**peak sensitivity matrix**

matrix with the components of peak sensitivity considered along the normal sensitivity axis as the diagonal terms and the components of peak sensitivity considered along the cross-sensitivity axis as the non-diagonal terms

3.1.39**sensitivity**

output change per unit change of input acceleration in either static or dynamic state

NOTE 1 Sensitivity in steady state of level 1 accelerometers is generally evaluated as the slope of the straight line that can be fitted by the least square method applied to input-output data obtained by varying the input within the measurement range.

NOTE 2 Sensitivity for level 2, 3 and 4 accelerometers is expressed by a matrix.

3.1.40**sensitivity error**

algebraic difference between a sensitivity of a device and the nominal sensitivity in the specification, with the percentage expression applied with the nominal sensitivity

NOTE The sensitivity of the device possesses the maximum and the minimum values among the over-all figures containing the temperature coefficient, etc.

3.1.41**temperature coefficient of sensitivity**

change in sensitivity per unit change in temperature relative to the sensitivity at the specified temperature

3.1.42**normal sensitivity**

sensitivity defined along the axis with the maximum sensitivity of an accelerometer

3.1.43**cross-sensitivity**

sensitivity defined by the output along the specified axis perpendicular to the input along the normal sensitivity axis

3.1.44**cross-axis sensitivity**

maximum sensitivity in the plane perpendicular to the measuring direction relative to the sensitivity in the measuring direction

NOTE 1 The maximum sensitivity in the perpendicular plane is obtained as the geometric sum of the sensitivities in two perpendicular directions in this plane.

NOTE 2 Transverse sensitivity can be used in stead of cross-axis sensitivity.

3.1.45

cross-coupling coefficient

ratio of the variation of accelerometer output to the product of acceleration applied normal and parallel to an input reference axis

3.1.46

peak sensitivity

value as the ratio of the maximum output signal divided by the maximum input acceleration

NOTE See Annex C.

3.1.47

frequency response of sensitivity

ratio of the output signal to the applied acceleration at discrete frequency or in narrow bandwidth as a function of frequency

3.1.48

frequency response of cross-sensitivity

ratio of the output signal to the applied acceleration at discrete frequency or in narrow bandwidth in orthogonal direction as a function of frequency

3.1.49

Doppler shift interferometer

interferometer based on Doppler shift principle

3.1.50

laser interferometer

system that measures a motion by means of an optical interference using a laser as a light source

NOTE It serves for the primary calibration of accelerometers.

3.1.51

strain gauge

sensor that electrically detects the strain

3.1.52

uncertainty

parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand

NOTE See Guide to the expression of uncertainty in measurement.

3.2 Letter symbols

For the purposes of this document, letter symbols given in Table 1, apply.

Table 1 – List of letter symbols

Name and designation	Letter symbol	Remarks
Acceleration: – at input points of $j = 1, \dots, n$ – of a positive specific input to DC accelerometer – of a negative specific input to DC accelerometer – of a specific input to AC accelerometer – of a positive maximum input – of a negative maximum input – due to local gravity – due to standard gravity	a_j a_+ a_- a_{rms} a_{max} a_{min} g g_n	$g_n = 9,806\ 65\ \text{m/s}^2$
Accelerometer output: – in accelerometer output units – at input-acceleration points of $j = 1, \dots, n$ – at a positive specific input a_+ – at a negative specific input a_- – at a specific input arms – at the UP(+1 g) position – at the DOWN(–1 g) position	E E_j E_+ E_- E_{rms} E_{up} E_{down}	
Bias: – apparent value – in the high temperature operating condition – in the low temperature operating condition – in the standard condition – at the 0 g position (0 g bias) – at the 1 g position (1 g bias) – temperature coefficient	B' B_{high} B_{low} B_{std} B_0 B_1 B_{tco}	
Bias discrepancy	B_d	
Deviation of the accelerometer output: – from the straight line at points of E_j – largest absolute value from the straight line	δE_j δE	
Linearity – for static linearity	SL	
Cross-coupling coefficient – for IRA and PA – for IRA and OA	K_p K_o	
Misalignment of the IA with respect to the IRA: – composite value – about the OA – about the PA	γ γ_o γ_p	
Sensitivity: – nominal value – apparent value – in the high temperature operating condition – in the low temperature operating condition – in the standard condition – temperature coefficient	S S' S_{high} S_{low} S_{std} S_{tco}	

Table 1 (continued)

Name and designation	Letter symbol	Remarks
Temperature:		
– in the high temperature operating condition	T_{high}	
– in the low temperature operating condition	T_{low}	
– in the standard condition	T_{std}	
– minimum value rated during the specified storage time	$T_{\text{stg min}}$	

4 Essential ratings and characteristics

4.1 General

4.1.1 Operating principle

The operating principle of semiconductor accelerometers is almost equal to that of other types of accelerometers. Accelerometers with heat convection as the operating principle might be considered an exception. Semiconductor accelerometers can be classified as piezo-resistive type, and capacitive type, etc. by considering the detection principle of seismic mass motion. The large variety seen in semiconductor accelerometers is due to the nature of the operating principles.

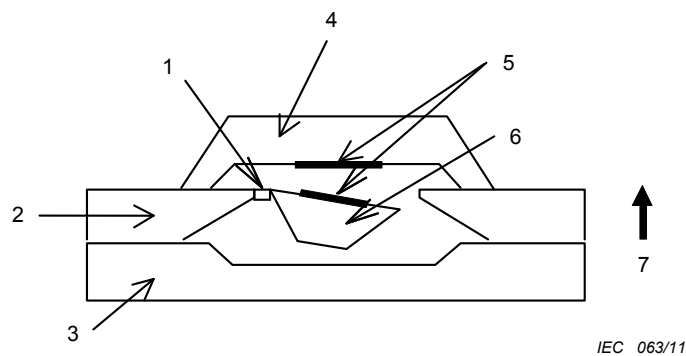
NOTE Capacitive type accelerometers include those having driving mechanism such as comb drive accelerometers, servo accelerometers and vibration beam accelerometers, etc.

4.1.2 Single axis and multi-axis

There exist both single-axis type and multi-axis type semiconductor accelerometers. Most of the technical aspects on the one-axis semiconductor accelerometers are covered by traditional standards on the subject. Since traditional acceleration devices were invented, the greatest innovation caused by semiconductor technology is the multi-axis accelerometers up to the six-axis. This standard is written based on the philosophy that not only single-axis accelerometers but also multi-axis accelerometers may be described within the same concept. The idea is simply that the acceleration is a vector quantity. The description given of one-axis accelerometers in this standard mainly comes from this idea, leading to the generation of differences from existing standards on accelerometers.

In these cases, each input axis (IA) for accelerometer mount surface should be defined in the co-ordinate system affixed to the specified accelerometer. The widely accepted idea that multi-axis accelerometers can measure acceleration as a vector has been re-examined, and mathematically investigated using a vector space theory. Both the theories and the practical techniques based on this concept are described in Annexes A to C.

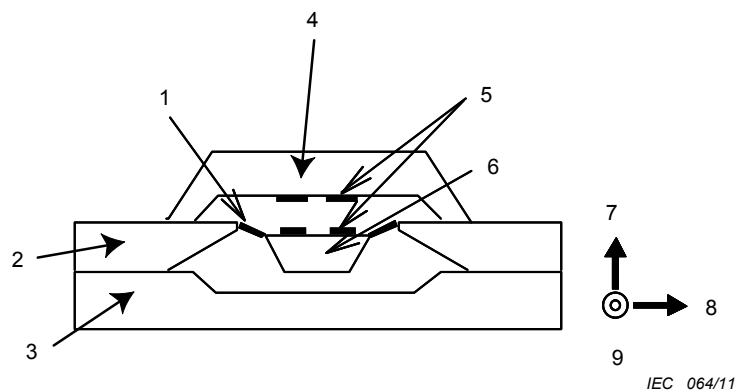
The following figures 1 and 2 show the typical structure of semiconductor accelerometers.



Key

1	flexure hinge	2	silicon	3	glass
4	glass	5	pick off electrode	6	proof mass
7	acceleration (Z)				

Figure 1 – Single axis accelerometer



Key

1	flexure hinge	2	Silicon	3	glass
4	glass	5	pick off electrode	6	proof mass
7	acceleration (Z)	8	acceleration (Y)	9	acceleration (X)

Figure 2 – Multi-axis accelerometer

This standard applies to semiconductor accelerometers with built-in electric circuits. It is not applicable to the sensing element alone because it does not generate any electric signals.

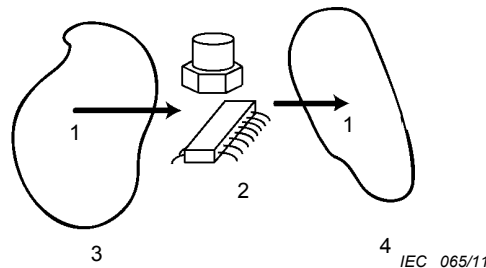
4.1.3 Performance evaluation

Performance evaluation of accelerometers should be carried out utilizing, in principle, inertia in local level co-ordinate systems. In some applications, care should be taken over the co-ordinate system transformation between the local level co-ordinate system and the inertia co-ordinate system. Local gravity or centripetal acceleration is recommended as the reference acceleration for measuring the sensitivity of DC accelerometers. To measure the sensitivity of AC accelerometers and the frequency response characteristics of DC accelerometers, it is recommended using a vibration generator and a laser interferometer for the primary calibration.

4.1.4 Sensitivity

The purpose of the accelerometer is to measure acceleration. This can be a definition of physical function of accelerometers. On the other hand, the definition of mathematical function of accelerometers is the projection of vector space of actual acceleration vectors to the output signal vector space, because acceleration is a vector quantity. Therefore, as linear

algebra indicates, only a matrix can define the sensitivity of accelerometers, since a matrix can transform a vector space into another vector space. Figure 3 shows the concept of the mathematical definition of accelerometers.



Key

- | | |
|------------------|-----------------------------------|
| 1 Dimension | 3 Input acceleration vector space |
| 2 Accelerometers | 4 Input acceleration vector space |

Figure 3 – Concept of the mathematical definition of accelerometers

“Dimension” in Figure 3 stands for the maximum number of linearly independent vectors in the vector space. Dimension of the space where the accelerometer sensitivity is defined is very important, because it is related to the size of the sensitivity matrix. The purpose of acceleration generation using machines for calibration such as vibration tables is to simulate the application acceleration vector space. Accelerometers shall be calibrated in the calibration acceleration vector space with the dimension that is normally larger than or equal to the dimension of the application acceleration vector space.

NOTE 1 For further details see Annex A.

NOTE 2 The concept shown in Figure 3 can be shared with the other vector quantity detection sensors such as gyros, IMUs, and force sensors.

4.1.5 Classification

It is evident that a matrix should describe the sensitivity of an accelerometer. However, it is not always practical to obtain the definition of sensitivity using a matrix at every instant, because it is not always the case that both direction and magnitude are measured. In some cases, the direction of motion is predictable using a priori information. A typical example might be the vibration of a beam with a very flat cross-section. On the other hand, the sensitivity of accelerometers for crash detection should be a matrix, because it is almost impossible to predict the direction of the crash. In order to cope with these real applications, this standard introduces the classification of accelerometers, as shown in Table 2.

Table 2 – Level of accelerometers and the definition

Level of accelerometers	Descriptions
Level 4 accelerometer	The sensitivity of level 4 accelerometers is defined as a matrix. All components in the matrix are defined as functions of frequencies
Level 3 accelerometer	The sensitivity of level 3 accelerometers is defined as a matrix. Some of the components in the sensitivity matrix are defined as functions of frequency. Non-diagonal components are not zero
Level 2 accelerometer	The sensitivity of level 2 accelerometers is defined as a matrix. All components of the matrix are constant with a clear frequency and specification including the nonzero non-diagonal terms
Level 1 accelerometer	The matrix sensitivity is not considered in level 1 accelerometers. The sensitivity along the input axis is separated from the cross axis sensitivity

NOTE 1 The ISO 16063 and ISO 5347 series standard might be applicable to level 1 accelerometers. The major purpose of the descriptions in this standard is to provide the technologies covered by neither the ISO 16063 series standard nor the ISO 5347 series standard.

NOTE 2 "Frequency" in Table 1 includes zero frequency, because DC accelerometers for levels 2, 3 and 4 possess matrix sensitivities at 0 Hz.

NOTE 3 All of the components of the static sensitivity matrix for level 2 to level 4 DC accelerometers are defined at 0 Hz. Each term of the static sensitivity matrix is the same in level 2, level 3 and level 4 accelerometers, i.e. if i and j of a_{ij} are equal to m and n of a_{mn} of the different level accelerometers, a_{ij} is equal to a_{mn} .

The technical aspects of this classification are as follows:

- The classification is regarded as the basic framework for accelerometers to meet the specific application requirement, neither introducing too much nor too little detail.
- All products fit the above description on the level of accelerometers.
- The classification should be applied to accelerometers with either angular velocity or angular acceleration detection capabilities.
- The classification is applicable to every accelerometer without any regard to the number of sensitivity axes.
- The classification clarifies whether the sensitivity is defined in the vector space or not.
- The classification describes the dimension of the vector space where the sensitivity of the accelerometer is defined.
- The classification is beneficial to customers who will recognize it as the fundamental performance criteria.

NOTE 4 See Annex A for further details.

NOTE 5 ISO/IEC 17025 clearly states that reference standards and calibration guaranteed by NMIs are not the only way for traceability. It states that the programme for calibration of equipment shall be designed and operated so as to ensure calibrations and measurements are traceable to the international System of Units (SI) (Système International d'unités). This standard provides the possibility of establishing the traceability of multi-axis accelerometers; i.e. calibration based on SI.

NOTE 6 The classification shown in Table 2 is applicable to gyros and IMUs.

4.1.6 Symbol (g)

In this standard, the symbol ' g ' is used for acceleration when calibration or test is carried out using local gravity.

4.1.7 Customer and supplier

This standard shall neither violate nor interfere with the agreement between customers and suppliers in terms of a new model or parameters for business.

4.1.8 Linearity and nonlinearity

In some cases, signals in the non-linear region of an accelerometer are used. This results from a strong demand for low production cost and special signal processing largely dependent on the application. In other cases, application requires a simulation model of semiconductor accelerometers in the system design stage, covering not only linearity but also non-linearity between input and output.

4.1.9 Element materials

Materials used for semiconductor accelerometers consist mainly of silicon. Ratings of semiconductor accelerometers depend on the element materials.

4.1.10 Handling precautions

Due to the fragile nature of sensing elements and electrical circuits, semiconductor accelerometers should not be subjected to an environment which exceeds the ratings. This is in order to avoid permanent changes in the specified characteristics. When handling the devices, the precautions given in Clause 8 of IEC 60747-1:2006 shall be referred to.

4.1.11 Accelerometer mounting condition

Outer packaging of accelerometers should have enough rigidity for their intended use. Suppliers should describe the requirements for the accelerometer mounting and mounting surface conditions in the specifications. Dynamic measurement described in this standard should be carried out under the recommended conditions.

NOTE A quantitative description concerning sufficient rigidity is described in each calibration measurement technique.

4.1.12 Specifications

Specifications for semiconductor accelerometers should contain the following:

- name of manufacturer, model;
- classification;
- dimensions, mass (weight) and package type, e.g. DIP;
- recommended mounting method;
- ratings, recommended operating conditions and characteristics as defined in 4.2 to 4.4.

4.2 Ratings (limiting values)

The following items should be described in the specification, unless otherwise stated in the relevant procurement specifications. Stresses over these limits may cause permanent damage to the devices:

- storage temperature range;
- storage humidity range;
- mechanical shock;
- supply voltage range;
- input acceleration limits;
- maximum supply voltage or current.

4.3 Recommended operating conditions

The following items should be described in the specification, unless otherwise stated in the relevant procurement specifications. These conditions are recommended in order to keep the characteristics of the devices stable during operation:

- operating temperature range;
- operating humidity range;
- operating acceleration range;
- nominal supply voltage.

4.4 Characteristics

4.4.1 General

Characteristics shall be measured at 25 °C, unless otherwise stated. Other temperatures should be taken from the list in Clause 5 of IEC 60747-1:2006.

4.4.2 Measurement range

Maximum and minimum acceleration values shall be as per the measurable acceleration values.

4.4.3 Sensitivity and sensitivity error

Sensitivity is defined as output change per unit change of input acceleration. It should be expressed by output signal (e.g. voltage) per unit input acceleration.

The sensitivity error for level 1 accelerometers is the algebraic difference between the sensitivity of a device and the nominal sensitivity in the specification, with the percentage deviation from the nominal sensitivity. Maximum and minimum values among the over-all figures containing the temperature coefficient etc. should be used.

For level 2, 3 and 4 accelerometers, the sensitivity error is expressed by a matrix. Every component in the sensitivity error matrix is the algebraic difference between the sensitivity matrix component and the corresponding nominal sensitivity matrix component in the specification, with the percentage deviation from the corresponding nominal sensitivity matrix components.

4.4.4 Bias (offset) and bias (offset) error

Bias is the output without any acceleration along the input axis. This may be represented by the algebraic means of the two outputs when the acceleration is applied in two directions, $+g$ and $-g$, along the input axis and with typical values.

Bias error is the algebraic difference between the bias of a device and the nominal bias in the specification. Maximum and minimum values among the overall figures containing the temperature coefficients should be used.

NOTE 1 Offset is also used in a similar way as bias.

NOTE 2 Offset error is also used in a similar way as bias error.

NOTE 3 Bias and bias error are independent from the classification of accelerometers.

4.4.5 Linearity

4.4.5.1 Linearity in DC acceleration measurement

Linearity is defined as the deviation of the output of a device from the straight line defined by the sensitivity. Percentage expression with the full scale of the specification and maximum values should be mentioned.

4.4.5.2 Linearity in sinusoidal acceleration measurement

Linearity in sinusoidal acceleration is concerned with both gain and phase. Gain linearity is defined as the maximum deviation of the gain of a device at each frequency from the straight line defined by the absolute value of the complex sensitivity in sinusoidal acceleration as a function of amplitude and frequency of an input signal. Phase linearity is defined as the maximum deviation of the phase of a device at each frequency from the straight line, defined by the phase of the complex sensitivity in sinusoidal acceleration, as a function of amplitude and frequency of an input signal. For details see Annex B.

4.4.6 Misalignment

This represents the angle between the input axis and the input reference axis indicated on the accelerometer package. Maximum values should be specified.

4.4.7 Cross-axis sensitivity

This should be described as the percentage expression of the sensitivity of specified input axis caused by the acceleration applied along the perpendicular direction to the specified input axis, with the input axis sensitivity.

NOTE 1 For matrix sensitivity see Annex A.

NOTE 2 This should be described by the non-diagonal terms of sensitivity matrix for level 2 to 4 accelerometers.

4.4.8 Cross-coupling coefficient

This coefficient is observed not only in a pendulum accelerometer with the open-loop control system but also in the cantilever accelerometer manufactured by micro-machining technology and is originated from inclination of input axis (e.g. pendulum or cantilever). This is one of the coefficients by which the deviations of the real output of a device from the straight line defined by the sensitivity are composed.

This coefficient is calculated by the Equation (8) in 5.2.8 from the data at the specific positions under the local earth's gravitation, g . The coefficient should be expressed by the maximum value.

4.4.9 Temperature coefficient of sensitivity

The maximum per cent change in sensitivity at +25 °C per unit change in temperature.

4.4.10 Temperature coefficient of bias

The maximum per cent change in bias at +25 °C per unit change in temperature.

4.4.11 Frequency response

Frequency response is a set of data or a diagram showing the amplitude ratio and phase shift between the input that changes sinusoidally over time and the sinusoidal output signal as a function of frequency. The frequency where the gain decreases to 3 dB below the maximum gain is called cut-off frequency, f_c and the minimum values should be mentioned. It should be noted that this concept is applicable only to a linear system.

NOTE For frequency response for level 2 to 4 accelerometers see Annex A.

4.4.12 Supply current

The supply current is specified under the condition of no load and normal temperature, +25 °C, unless otherwise specified.

4.4.13 Output noise

This comprises the AC components included in the output signal on the steady-state operation. This should be expressed either as an r.m.s. value in a specified frequency bandwidth, or as volt per square root of frequency.

4.4.14 Ratiometricity

This represents the linearity of the accelerometer output to the supply voltage change. It should be clearly stated if capability of ratiometricity exists or not. The output quantity

variations due to the supply voltage variations may be estimated through this figure, deviation from the linearity. Ratiometricity is expressed as either the maximum (volts) or percentage.

4.4.15 Self test

This is to check the proper functionality of the accelerometer without any real acceleration. Functionality is judged by measuring the electrical output when the specified electrical signal is applied to the specified terminals of the accelerometer. Self test should be specified by stating the input electrical signal to the self test terminals, the electrical outputs for judgement and the designated area covered by the self test.

5 Measuring methods

5.1 General

Measurement is divided into two categories:

- test,
- calibration.

The difference between test and calibration is made by the traceability to the national standards. Calibration is the measurement carried out using the instrumentation traceable to the authorized national standard equipment and techniques written in the specified document.

Uncertainty is indispensable in calibration. Test is more practical than calibration, because it can be done based on the negotiation between manufacturers and customers without traceability to national standard. However, it should be noted that the measurement techniques for calibration could be utilised for test. The basics used for the calibration or test should be documented, if the corresponding standard does not exist.

5.1.1 Standard test conditions

Standard test conditions are as follows:

- a) temperature: $25\text{ °C} \pm 5\text{ °C}$
- b) relative humidity: 45 % to 75 %, where appropriate
- c) air pressure: 86 kPa to 106 kPa, (860 mbar to 1060 mbar)
- d) nominal supply voltage $A\text{ V} \pm B\text{ V}$. Supply voltage A and its tolerance B shall be determined in individual specifications.

The electrical precautions are described in Clause 6 of IEC 60747-1:2006 and the standard test conditions recommended are in accordance with Clause 5 of IEC 60747-1:2006. The accelerometer and test equipment shall be brought to the operating condition with the specified acceleration input. The accelerometer and the immediate environment shall be allowed to reach thermal equilibrium so that the output of the accelerometer may be stabilized with the required accuracy before proceeding with the test.

5.1.2 Applicable measurement methods for test and calibration method

The standard temperature condition for calibration is $23\text{ °C} \pm 3\text{ °C}$. Relative humidity and air pressure are the same as shown in 5.1.1. Table 3 shows the relation between a test item and the recommended corresponding measurement methods. Table 4 shows the relation between a type of accelerometers and recommended corresponding applicable calibration methods.

Table 3 – Test items and the recommended corresponding measurement methods

Type	Test item	Gravitational acceleration		Centripetal acceleration		Vibration		Shock acceleration	
		Dividing head	Surface table	Single	Double	Sinusoidal vib.	Random vib.	Vib.	Elastic pulse
DC accelerometer	Measurement range			X	X	X	X	X	X
	Sensitivity	X	X	X	X	X	X	X	X
	Bias and bias error	X	X	X	X	X	C	c	c
	Static linearity	X	X	X	c	c	C	c	c
	Dynamic linearity				X	X	X	X	X
	Cross-axis sensitivity	X	X	X	X	X	X	X	X
	Cross coupling coefficient	X	X	Z	Z	Z	Z	Z	Z
	Temperature coefficient sensitivity	X	X	X	X	X	X	X	X
	Temperature coefficient of bias	X	X	X	X	Z			
	Frequency response	c	c	c	X	X	X	X	X
AC accelerometer	Measurement range	c	c	c	X ^a	X	X	X	X
	Sensitivity	c	c	c	X	X	X	X	X
	Bias and bias error	c	c	c	X	Z ^b			
	Dynamic linearity	c	c	c	X	X	X	X	X
	Cross-axis sensitivity	c	c	c	X	X	X	X	X
	Cross coupling coefficient	c	c	c	Z	Z	Z	Z	Z
	Temperature coefficient sensitivity	c	c	c	X	X	X	X	X
	Temperature coefficient of bias	c	c	c	Z	Z	c	c	c
	Frequency response	c	c	c	X	X	X	X	X
^a X = Test item is covered by the method marked X. ^b Z = Test item is not stated in this standard. ^c Blank = The method is essentially not applicable to the specified test item.									

Table 4 – Relation between recommended applicable calibration methods and type of accelerometers

Type		No. of axis	Dividing head		Centrifuge		Dimension (vibration)		Shock acceleration	
			Four point	Two point	Single	Double	One	Three	Vib.	Elastic pulse
DC accelero meter	Level 1	1	X ^a	X	X	X	X	X	X	X
		2	X	b	X	X	X	X	X	X
		3	X	b	X	X	X	X	X	X
	Level 2	1	X	b	X	X	X	X	X	X
		2	X	b	X	X	X	X	X	X
		3	X	b	X	X	X	X	X	X
	Level 3	1	X	b	X	X	X	X	X	X
		2	X	b	X	X	X	X	X	X
		3	X	b	X	X	X	X	X	X
	Level 4	1	X	b	X	X	X	X	X	X
		2	X	b	X	X	X	X	X	X
		3	X	b	X	X	X	X	X	X
AC accelero meter	Level 1	1	b	b	b	X	X	X	X	X
		2	b	b	b	X	X	X	X	X
		3	b	b	b	X	X	X	X	X
	Level 2	1	b	b	b	X	X	X	X	X
		2	b	b	b	X	X	X	X	X
		3	b	b	b	X	X	X	X	X
	Level 3	1	b	b	b	X	X	X	X	X
		2	b	b	b	X	X	X	X	X
		3	b	b	b	X	X	X	X	X
	Level 4	1	b	b	b	X	X	X	X	X
		2	b	b	b	X	X	X	X	X
		3	b	b	b	X	X	X	X	X
^a X = Test item is covered by the method marked X.										
^b Blank = The method is essentially not applicable to the specified test item.										

5.2 Testing methods for characteristics

5.2.1 Measurement range

The accelerometer shall be installed on the well defined, mechanical motion-generating equipment so that the acceleration may be applied along the input axis.

The accelerometer shall be operated under the standard test conditions of 5.1.

- Apply the positive maximum acceleration, $a_{\max}$. Record the accelerometer output E_+ .
- Apply the negative maximum acceleration, $a_{\min}$. Record the accelerometer output E_- .
- The difference between E_+ and E_- divided by the nominal sensitivity S shall conform to the individual specification.

5.2.2 Supply voltage range

The accelerometer shall be operated under the standard test conditions of 5.1.

- a) Apply the maximum supply voltage to the accelerometer, measure the measurement range, the sensitivity and the bias.
- b) Apply the minimum supply voltage to the accelerometer, measure the measurement range, the sensitivity and the bias.

The measurement range, the sensitivity and the bias shall conform to the requirement of the individual specification.

5.2.3 Sensitivity and sensitivity error

The accelerometer shall be installed on the well-defined mechanical motion-generating equipment so that the acceleration may be applied along the input axis. Unless otherwise specified, the accelerometer shall be operated under the standard test conditions of 5.1.

- a) Apply the necessary and sufficient number of positive acceleration with approximately equal increments ending the positive measurement range value.
- b) The number of acceleration applied might be selected by considering many factors such as required accuracy of the target accelerometer and efficiency of measurement etc. Record the input acceleration and the accelerometer output, E_j at each of the input accelerations.
- c) Apply the necessary and sufficient number of negative acceleration with approximately equal decrements ending the negative measurement range value.
- d) Calculate the value of the scale factor, S' , as the slope of the least squares straight line fit to the data points obtained by a) and b) above.

$$E_j = S'a_j + B' \quad (1)$$

$$S' = \frac{(n \sum a_j E_j - \sum a_j \sum E_j)}{n \sum (a_j)^2 - (\sum a_j)^2} \quad (2)$$

The sensitivity error shall include temperature coefficient of sensitivity, defined by 4.2.9, supply voltage coefficient of sensitivity and pressure coefficient of sensitivity, etc.

The sensitivity shall conform to the requirement of the individual specification.

An alternate method of measuring the sensitivity is to obtain accelerometer outputs at two or four cardinal positions using the local gravitational acceleration.

See Annex C concerning the method of measuring the peak sensitivity.

5.2.4 Bias and bias error

From the data obtained in 5.2.3, determine the algebraic sum of the outputs, E_{0+} , E_{0-} , when zero input is approached from each of the full scales. Calculate the value of the bias as follows:

$$B' = \frac{(E_{0+} + E_{0-})}{2S'} \quad (3)$$

Bias error shall include temperature coefficient of the bias, defined by 5.2.10, supply voltage coefficient of the bias and pressure coefficient of the bias, etc.

The bias and bias error shall conform to the requirement of the individual specification.

NOTE Deletion of S' in the denominator of the Equation (3) stands for offset.

5.2.5 Linearity

5.2.5.1 Static linearity

From the data obtained in 5.2.3, determine the deviations of the data points δE_j as follows:

$$\delta E_j = E_j - S'a_j - B' \quad (4)$$

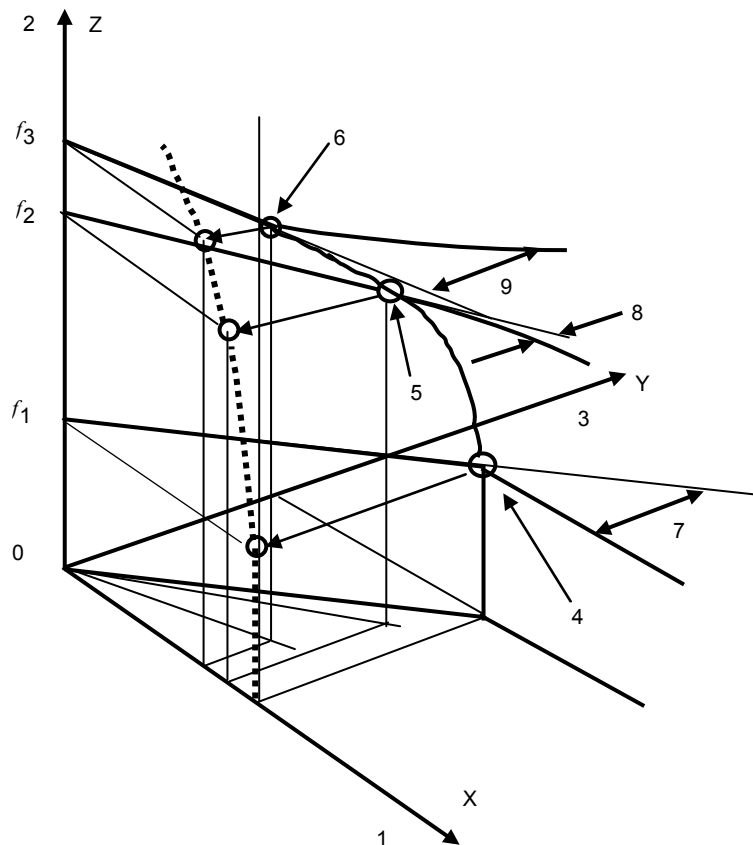
Select the largest absolute valued δE_j as δE , then calculate the linearity SL as follows:

$$SL = \frac{\delta E}{(a_{\max} - a_{\min})} \times 100 \% \quad (5)$$

The linearity SL shall conform to the requirement of the individual specification.

5.2.5.2 Dynamic linearity

5.2.5.2.1 Dynamic linearity on gain



IEC 066/11

Key

- | | |
|--|--|
| 1 X-axis, input acceleration amplitude | 6 limit of gain dynamic linearity at frequency f_3 |
| 2 Z-axis, frequency | 7 deviation from linearity at frequency f_1 |
| 3 Y-axis, accelerometer output signal amplitude | 8 deviation from linearity at frequency f_2 |
| 4 limit of gain dynamic linearity at frequency f_1 | 9 deviation from linearity at frequency f_3 |
| 5 limit of gain dynamic linearity at frequency f_2 | |

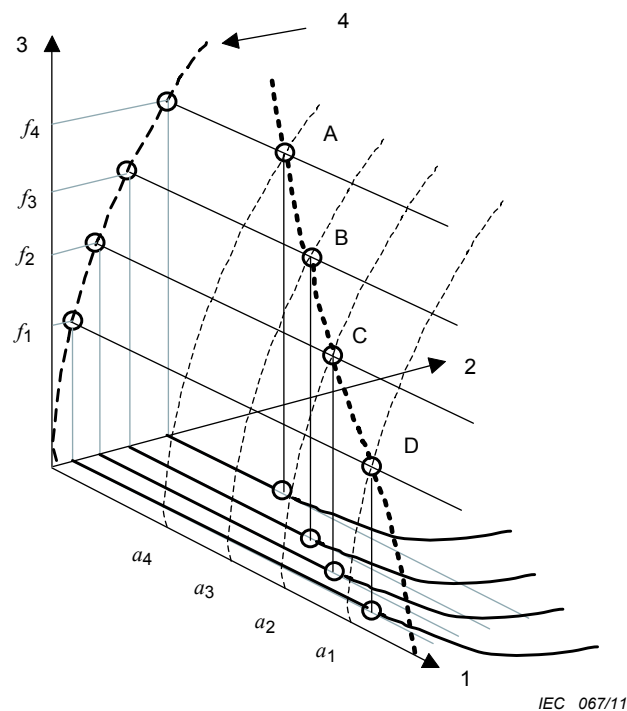
Figure 4 – Concept of dynamic linearity of an accelerometer on gain

The concept of linearity is usually shown as a relationship between DC acceleration input and the output acceleration signal from an accelerometer at the steady state. However, linearity is also an important concept in terms of dynamic response. Unless dynamic linearity is clearly defined, frequency response measurement does not make sense.

Figure 4 shows the concept of gain dynamic linearity as a function of input acceleration amplitude, output amplitude from accelerometer and frequency. Limit of gain dynamic linearity of an accelerometer is defined as a trajectory in the space with the X-axis as a function of input acceleration amplitude, the Y-axis as a function of output acceleration, and the Z-axis as a function of frequency. The projection of the trajectory to X-Z plane can define a region where the gain dynamic linearity holds. The boundary specifies the maximum input acceleration under the given maximum frequency or maximum frequency under the given maximum input acceleration amplitude.

5.2.5.2.2 Dynamic linearity on phase

Dynamic phase linearity is defined, based on the following diagram:



Key

- 1 X-axis, amplitude of input acceleration
- 2 Y-axis, phase of output from an accelerometer
- 3 Z-axis, frequency
- 4 relationship between frequency and phase lag when the input amplitude is very close to zero

Figure 5 – Concept of dynamic linearity of an accelerometer on phase

As long as the dynamic linearity on phase holds, the phase lag at each frequency is not dependent on the amplitude of the input acceleration to an accelerometer. However, as the input amplitude of acceleration to an accelerometer increases, phase lag will change from the constant value when the value is small. The dynamic linearity on phase is defined by the three-dimensional curved surface surrounded by the curve on the Y-Z plane, i.e. the relationship between frequency and phase lag when the amplitude of input acceleration to an accelerometer is very close to zero, the three-dimensional curve A, B, C and D, and the X-axis, i.e. axis of amplitude of input acceleration. The curve specifies the maximum input acceleration amplitude under a given frequency for dynamic linearity. It also specifies the maximum frequency under a given maximum acceleration amplitude. For instance, in Figure 5, if frequency f_3 is given as a maximum frequency, the upper limit of the input acceleration should be a_3 for dynamic linearity on phase.

5.2.6 Misalignment

The accelerometer shall be operated under the standard test conditions of 5.1, unless otherwise specified.

- a) The accelerometer shall be installed on the acceleration generating equipment so that the acceleration may be applied along the pendulum reference axis.
- b) Apply a positive specific acceleration and record the accelerometer output.
- c) Apply a negative specific acceleration and record the accelerometer output.
- d) Calculate the misalignment angle, γ_p .

- e) The accelerometer shall be installed on the acceleration generating equipment so that the acceleration may be applied along the output reference axis.
- f) Repeat the above procedures b), c) and d), and calculate the misalignment angle, γ_0 .

The value of misalignment angle shall conform to the requirements of 4.4.5.

5.2.7 Cross-axis sensitivity

The accelerometer shall be operated under the standard test conditions of 5.1, unless otherwise specified.

- a) The accelerometer shall be installed on the acceleration generating equipment so that the acceleration may be applied along the pendulum reference axis.
- b) In the case of DC accelerometers, apply a positive specific acceleration, a_+ and record the accelerometer output, E_+ ; apply a negative specific acceleration, a_- and record the accelerometer output, E_- .
- c) In the case of AC accelerometers, apply a specific acceleration, a_{rms} and record the accelerometer output, E_{rms} .
- d) Calculate the cross-sensitivity K_{cp} for pendulum reference axis using the following algebraic definitions:

$$K_{cp} = (E_+ - E_-)/(a_+ - a_-)/S \quad g/g \text{ (for DC accelerometers)} \quad (6)$$

$$K_{cp} = (E_{rms}/a_{rms})/S \quad g/g \text{ (for AC accelerometers)} \quad (7)$$

- e) The accelerometer shall be installed on the acceleration generating equipment so that the acceleration may be applied along the output reference axis.
- f) Repeat b), c) and d) for the output reference axis to obtain the cross-sensitivity K_{co} .
- g) The cross-axis sensitivity is calculated as a square root of the sum of the squares of K_{co} and K_{cp} .

The value of cross-axis sensitivity shall conform to the requirements of 4.4.6.

5.2.8 Cross-coupling coefficient

The accelerometer shall be operated under the standard test conditions of 5.1, unless otherwise specified.

- a) The accelerometer should be installed on the acceleration generating equipment so that the acceleration may be applied along both the input axis and the pendulum axis.
- b) For DC accelerometers, apply a specific acceleration, $0,707g$ and record the accelerometer outputs, E_1 and E_2 at 45° position and 225° position respectively by the multi-point test. Apply a specific acceleration, $0,707g$ and record the accelerometer outputs, E_3 , E_4 at 135° position and 315° position, respectively.
- c) Calculate the cross-coupling coefficient K_p using the following algebraic definition:

$$K_p = \left(\frac{E_1}{1g \sin \theta_1 \times 1g \cos \theta_1} + \frac{E_2}{1g \sin \theta_2 \times 1g \cos \theta_2} - \frac{E_3}{1g \sin \theta_3 \times 1g \cos \theta_3} - \frac{E_4}{1g \sin \theta_4 \times 1g \cos \theta_4} \right) \times \frac{1}{2S} \quad g/g^2 \quad (8)$$

where $\theta_1 = 45^\circ$, $\theta_2 = 225^\circ$, $\theta_3 = 135^\circ$, $\theta_4 = 315^\circ$.

- d) The accelerometer shall be installed on the acceleration generating equipment so that the acceleration may be applied along both the input axis and the output axis.

- e) Repeat the above procedures b), c) to calculate the cross-coupling coefficient K_o for this position.

The value of cross-coupling coefficient shall conform to the requirements of 4.4.7.

5.2.9 Temperature coefficient of sensitivity

- a) Mount the accelerometer in a temperature-controlled chamber with the standard test conditions of 5.1. Stabilize the accelerometer temperature at $25\text{ °C} \pm 5\text{ °C}$.
- b) Measure the sensitivity in accordance with 5.2.3.
- c) Repeat these measurements at the high operating temperature and the low operating temperature, as defined in 4.3.1.
- d) Calculate the temperature coefficient of the sensitivity, S_{tco} as follows:

$$S_{tco} = \frac{\left(\frac{S_{\text{high}} - S_{\text{std}}}{S_{\text{std}}} \right)}{T_{\text{high}} - T_{\text{std}}} \times 100\text{ \%}/\text{°C} \quad (9)$$

$$S_{tco} = \frac{\left(\frac{S_{\text{low}} - S_{\text{std}}}{S_{\text{std}}} \right)}{T_{\text{low}} - T_{\text{std}}} \times 100\text{ \%}/\text{°C} \quad (10)$$

- e) The temperature coefficient of the sensitivity takes the larger figure of the above definitions (9) and (10).

The value of the temperature coefficient of sensitivity shall conform to the requirement of the individual specification.

5.2.10 Temperature coefficient of bias

- a) Mount the accelerometer in a temperature-controlled chamber with the standard test conditions of 5.1. Stabilize the accelerometer temperature at $25\text{ °C} \pm 5\text{ °C}$.
- b) Measure the bias in accordance with 5.2.4.
- c) Repeat these measurements at the high operating temperature and the low operating temperature, as defined by 4.3.1.
- d) Calculate the temperature coefficient of the bias, B_{tco} as follows:

$$B_{tco} = (B_{\text{high}} - B_{\text{std}})/(T_{\text{high}} - T_{\text{std}}) \quad g/\text{°C} \quad (11)$$

$$B_{tco} = (B_{\text{low}} - B_{\text{std}})/(T_{\text{low}} - T_{\text{std}}) \quad g/\text{°C} \quad (12)$$

- e) The temperature coefficient of the bias takes the larger figure of the above definitions (11) and (12).

The value of the temperature coefficient of the bias shall conform to the requirement of the individual specification.

5.2.11 Frequency response

5.2.11.1 Mechanical considerations

Input acceleration to an accelerometer shall be clearly and explicitly defined for the whole range of frequency response characteristic measurement with the uncertainty that enables the final specified uncertainty of the characterization. With this in mind, it is not recommended to utilise a back-to-back reference accelerometer for the characterization of an accelerometer by impact.

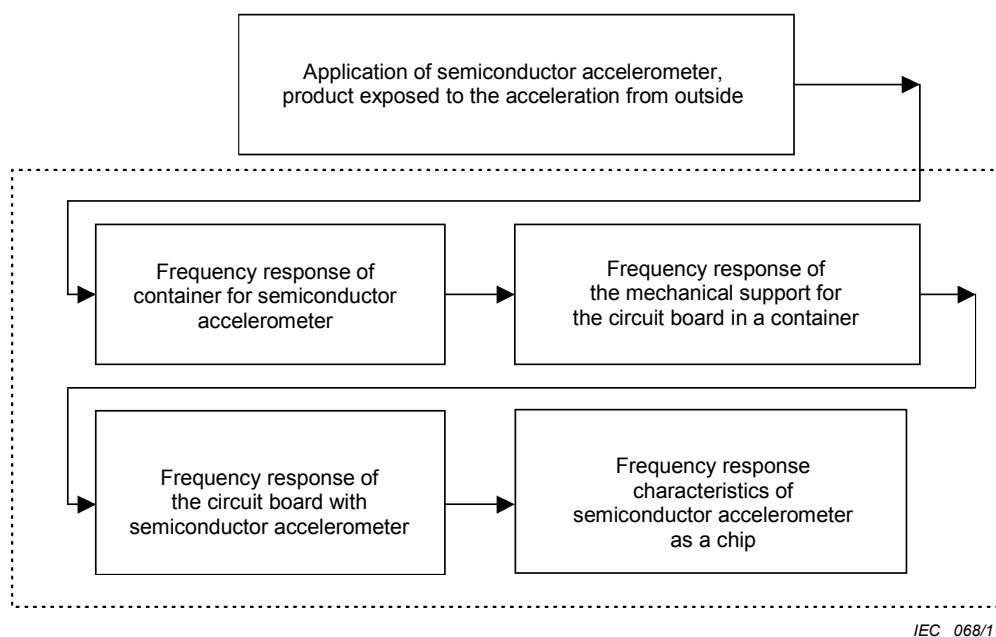
The implicit assumption on reference accelerometers is that the rigidity of the casing is infinite and that the motion of the front end surface and the back end surface are always in the same phase. This is of course impossible. Manufacturers of de facto standard accelerometers do not provide the information on the limit of the frequency and acceleration level under which the motion of the same phase holds. It also should be noted that the de facto standard piezoelectric accelerometers available on the market are only one-dimensional under the calibration authorisation with one-dimension capability. Assembled three-dimensional accelerometers using one-dimensional piezoelectric accelerometers are not calibrated using the three-dimensional motion.

If the target accelerometer is of a semiconductor multi-axis type, it is absolutely necessary to add acceleration along each sensitive axis of the accelerometer independently. The acceleration vibration component whose axis is vertical to the sensitive axis of the target accelerometer shall be clearly stated in the report of the frequency response characteristic measurement. Since the off-axis sensitivity or cross-axis sensitivity is a function of frequency, simultaneous and independent excitation of the vibration motion perpendicular to the main axis motion is indispensable.

It is hardly possible to add acceleration directly to the semiconductor accelerometer chips defined in Clause 3. They are soldered on the PC board accompanied by other electronic devices, amplifiers and discrete devices. The board may be mechanically supported and placed in a container, which might be connected to the structures of the target application. Therefore, it should be noted that the frequency response characteristics of semiconductor accelerometers is measured with regards to the system, including not only the target semiconductor accelerometer but also PC board with electronic devices and a mechanical support component. Therefore, it should be noted that two systems with the same accelerometer chips but with different support, or fixing mechanism, and different PC boards are dissimilar.

If the frequency response characteristic measurement is concerned with the accelerometer module whose mechanical structure is different from that of the real application, the compensation of the mechanical structure difference shall be carried out. If the target accelerometer is of multi-axis type and if the compensation of the frequency response of mechanical structure difference is required, it shall be noted that the measurement is valid within the frequency range where compensation data is available along all of the axis of the accelerometer.

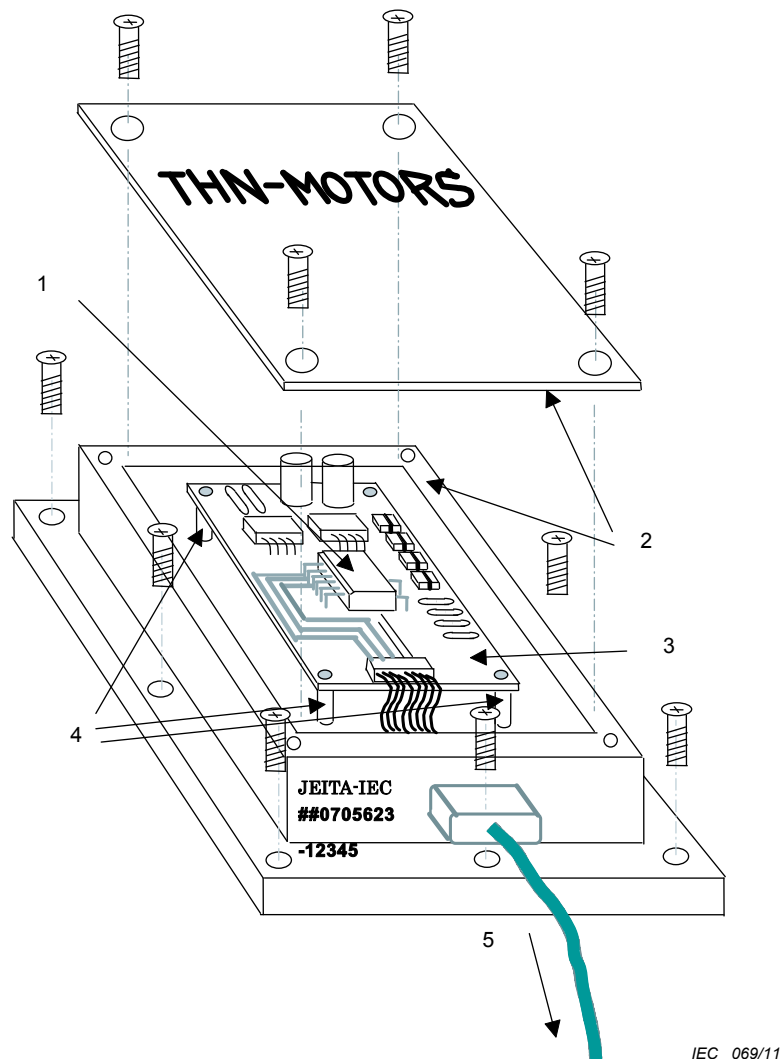
It should be strongly noted that the frequency response is measured in the domain where the dynamic linearity of accelerometers is guaranteed. Though the measurement of dynamic linearity using a vibration generator is rather tedious, it is, in principle, indispensable. Also in the shock acceleration measurement, dynamic linearity is very important in terms of the resonant frequency. This standard describes dynamic linearity as the basis of the measurement of frequency response measurement.



NOTE The target of the frequency response characteristic measurement is the system circled by the dotted line.

Figure 6 – The semiconductor accelerometer as a system

Figure 7 gives an example of the structure of assembled semiconductor accelerometer system for the concept of accelerometer frequency response.



Key

- 1 accelerometer
- 2 container for circuit board with accelerometer chip, electrical circuits and cables
- 3 circuit board
- 4 support
- 5 cable

Figure 7 – Example of the structure of assembled semiconductor accelerometer system for the concept of accelerometer frequency response

5.2.11.2 Electrical considerations

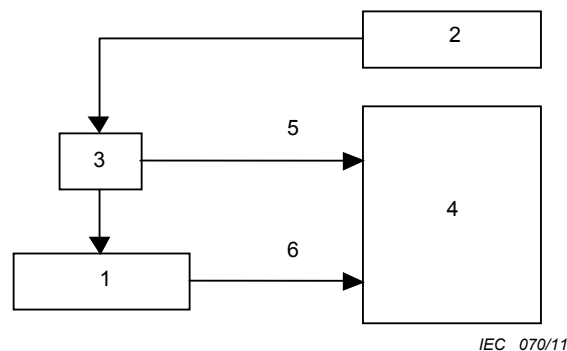
The purpose of the method shown here is to obtain the response of the target accelerometer to the applied electrical signals corresponding to the real accelerations. The electrical signals should have the required frequency components.

Although this method is suitable for the low-frequency response measurement for closed loop accelerometers, with appropriate accuracy consideration, it can be applied to either higher frequency regions or open loop accelerometers. As this method can provide frequency

response characteristics of the semiconductor accelerometer as a chip, without being influenced by the packaging, the circuit boards and containers, it may be used for in-process inspection by accelerometer manufacturers along with the self test.

The accelerometer shall be operated under the standard test conditions of 5.1 unless otherwise specified.

- a) Set up the measuring apparatus as shown in Figure 8.
- b) Apply electrical signal and measure signal of channel A and channel B.
- c) Calculate the gain and phase characteristic using the obtained data.



Key

- | | |
|------------------------|--------------------|
| 1 target accelerometer | 2 signal generator |
| 3 input monitor device | 4 signal analyser |
| 5 channel A | 6 channel B |

Figure 8 – Schematic diagram of frequency response measurement by electrical input

5.2.12 Supply current

Unless otherwise specified, the accelerometer shall be operated under the standard test conditions of 5.1.1.

- a) Connect the current measuring devices and apply power as specified in 5.1.1 d).
- b) Record the current from each source.

The value of the supply current shall conform to the requirement of the individual specification.

5.2.13 Output noise

Unless otherwise specified, the accelerometer shall be operated under the standard test conditions of 5.1.1.

- a) Connect the output to the spectrum analysis equipment and apply power as specified in 5.1.1 d).
- b) Record the r.m.s. value in a specified analysis bandwidth V_{rms}/Hz and express as volt per square root of hertz $V/\sqrt{\text{Hz}}$.

The value shall conform to the requirement of the individual specification.

6 Acceptance and reliability

6.1 General

The test in this clause shall, in general, be in accordance with the IEC 60749 series and, for test procedures, in accordance with the IEC 61000-4 series.

Test conditions such as temperature, humidity and so on should be in accordance with IEC 60749-1 unless otherwise stated in the relevant procurement specification.

6.2 Environmental test

6.2.1 High temperature storage

IEC 60749-6, with some modification, is applicable for this test procedure.

Storage temperature shall be the maximum storage temperature as given in the relevant specification.

For storage duration, IEC 60749-6 is applicable, unless otherwise stated in the relevant specification.

6.2.2 Low-temperature storage

6.2.2.1 General

This subclause provides the methods to evaluate the endurance of semiconductor accelerometers when stored at low temperature for a long time.

Since the IEC 60749 series does not provide any standard for a low-temperature storage test, the following test procedures are recommended.

6.2.2.2 Test equipment

The chamber to be used in this test shall keep the test temperature at the value specified in 6.1.2.3.2 and within the tolerances given. In this case, the chamber shall be constructed so that the specimen may not be exposed to direct radiation from the cold source during the test.

6.2.2.3 Procedure

6.2.2.3.1 Initial measurement

Initial measurement shall be carried out in conformity with the items and conditions specified in the detailed specification.

6.2.2.3.2 Test

Store the specimen in the thermostatic chamber and pre-set at the specified low temperature for the specified time. The storage temperature should be the minimum rated temperature, $T_{\text{stg min}}$, unless otherwise specified.

The allowance of the storage temperature should be $\pm 5^\circ\text{C}$ at a temperature lower than -25°C , and from $+3^\circ\text{C}$ to -5°C at a temperature not lower than -25°C .

The test duration should be 1 000 h, unless otherwise specified.

6.2.2.3.3 Post treatment

After finishing the test, take the specimen out of the thermostatic chamber, and leave it standing under standard conditions for 2 h to 24 h so that the specimen may reach thermal equilibrium.

Frost or water droplets on the specimen should be removed beforehand.

6.2.2.3.4 End-point measurement

Carry out the end-point measurement in conformity with the items and conditions specified in the detail specification.

Information to be given in the detailed specification is as follows:

- a) Items and conditions of the initial measurements given in 6.1.2.3.1.
- b) Storage temperature, if it is different from $T_{\text{stg min}}$, given in 6.1.2.3.2.
- c) Test duration if different from 1 000 h given in 6.1.2.3.2.
- d) Post treatment, if compulsory and not given in 6.1.2.3.3.
- e) Items and conditions of end-point measurements, as given in this subclause.

6.2.3 Temperature humidity storage

IEC 60749-5 is applicable without bias voltage for this test procedure, unless otherwise stated in the relevant specification.

6.2.4 Temperature cycle

IEC 60749-25 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

6.2.5 Thermal shock

IEC 60749-11 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

6.2.6 Salt mist

IEC 60749-13 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

6.2.7 Vibration

IEC 60749-12 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

6.2.8 Mechanical shock

IEC 60749-10 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

6.2.9 Electrical noise immunity

IEC 61000-4-4 is applicable for this test procedure.

6.2.10 Electro-static discharge immunity

IEC 61000-4-2 is applicable for this test procedure.

6.2.11 Electro-magnetic field radiation immunity

IEC 61000-4-3 is applicable for this test procedure.

6.3 Reliability test

6.3.1 Steady-state life

IEC 60749-6, with some modification, is applicable for this test procedure, unless otherwise stated in the relevant specification.

The principal test conditions in this standard are as follows:

- a) ambient temperature to be the maximum operating ambient temperature according to the ratings of the devices;
- b) application of the nominal or maximum supply voltage according to the ratings of the device;
- c) no acceleration along the input axis of the device.

6.3.2 Temperature humidity life

IEC 60749-5 is applicable for this test procedure, unless otherwise stated in the relevant specifications.

The principal test conditions in this standard are as follows:

- a) application of the nominal or maximum supply voltage according to the ratings of the device;
- b) no acceleration along the input axis of the device.

Annex A (informative)

Definition of sensitivity matrix of an accelerometer

A.1 Introductory remarks

One of the new aspects of the semiconductor accelerometer is the intrinsic mechanical structure for the measurement of acceleration as a vector. Classical three-axis accelerometer is a combination of three one-axis accelerometers calibrated using a one-dimensional vibration generator.

Normally, the sensitivity axis of one-axis accelerometers is always along the direction of vibration motion. However, it should be noted that the calibration of a one-axis accelerometer using a one-axis vibration table is very contradictory, because the direction is not taken into account. The measurement of acceleration is the measurement of amplitude and direction, because acceleration is a vector quantity. Since the one-axis vibration generator cannot clarify cross-axis sensitivity of one-axis accelerometers as a function of frequency, combining three one-axis accelerometers along the orthogonal co-ordinate system cannot be a physically rigorous method of measuring acceleration as a vector. Therefore three-axis accelerometers differ from three-dimensional accelerometers that can measure acceleration as a vector defined in the three-dimensional space with three degrees of freedom. The conventional technique can only calibrate level 1 accelerometers, even though it has long been accepted. This comes from the fact that almost all of the vibration tables have possessed only a single axis. This is obviously from the point of view that the vibration table is a machine that generates the input acceleration vector space.

This standard describes the sensitivity as a matrix, defining a relationship between the input acceleration vector space and the accelerometer output vector space. Though an acceleration vector includes not only translational but also rotational components, the current vibration generator is not yet mature enough for precision motion with six degrees of freedom. The sensitivity matrix is therefore derived in terms of translational acceleration in the beginning.

NOTE 1 It should be noted that sensitivity matrix can be applied to any multi-axis accelerometers. This includes, of course not only multi-axis semiconductor accelerometers but also assembled three-axis accelerometers where three, one-axis piezoelectric accelerometers or servo-accelerometers are fixed on the block stage in the orthogonal co-ordinate system. The essential difference between semiconductor multi-axis accelerometers and the conventional multi-axis accelerometers is the number of seismic systems in the multi-axis accelerometer. Most of the semiconductor multi-axis accelerometers possess only single seismic systems with multi-dimensional acceleration sensitivity.

NOTE 2 The space where an accelerometer is calibrated can have maximally six dimensions. Even if the normal motion space where the accelerometers are applied is a translational motion space with three degrees of freedom in design, the abnormal situations such as natural disasters or accidents can generate the rotational motion, i.e. the motion spaces with larger dimensions than that assumed in design. Apparently, it is expensive to calibrate accelerometers in the vector space with dimensions which are larger than 1. However, it is impossible to dismiss the advent of multi-axis semiconductor accelerometers such as three-axis, five-axis or six-axis in the market. This trend has clarified the gap of the measurement quality of the characterization techniques between what is available at present and what shall be available in the future. Moreover, one cannot prevent the development of motion space generation machines for the six-dimension vector space which is enjoying global success. For these reasons, this annex describes the sensitivity of an accelerometer in the form of a matrix derived in the vector space with the dimension three or six.

NOTE 3 As was stated in 5.2.1 measurement range, conventional acceleration measurement has assumed that the acceleration is applied along the input axis. This is reasonable only when an input axis is single and the direction of motion is always predictable. It does not make sense to apply the acceleration along one of the input axes of multi-axis accelerometers. As long as the acceleration is a vector quantity, measuring acceleration using accelerometers means measuring both magnitude and direction with a component expression. Therefore, the conventional calibration technique for accelerometers would not contribute to the acceleration measurement when neither the amplitude nor the direction is known.

NOTE 4 ISO 2041 states that acceleration is a vector quantity.

NOTE 5 Annex A, is applicable to semiconductor gyros, semiconductor gyros with acceleration detection capability and inertial measurement units, so called IMU.

A.2 Basics

A.2.1 Mathematical formulation

A.2.1.1 Formulation of three-axis accelerometer

Since acceleration is a vector quantity, the matrix notation of sensitivity of an accelerometer is generally accepted. As long as the sensitivity of a three-axis accelerometer is acknowledged, then the sensitivity of an accelerometer as a function of frequency and in the form of a matrix has to be defined. The fundamental assumption is the linearity in the neighbourhood of the equilibrium point. Assuming that the sensitivity matrix is only valid at the specified mounting can solve the difficulty that mechanical balance is dependent on how an accelerometer is installed.

Input acceleration shall be defined as a vector as follows:

$$\begin{aligned} \mathbf{A}_{\text{input}}(t) &= \begin{pmatrix} a_{g,x}(t) \\ a_{g,y}(t) \\ a_{g,z}(t) \end{pmatrix} \\ \mathbf{A}_{\text{outout}}(t) &= \begin{pmatrix} a_{s,x}(t) \\ a_{s,y}(t) \\ a_{s,z}(t) \end{pmatrix} \end{aligned} \quad (\text{A.1})$$

where $\mathbf{A}_{\text{input}}(t)$ and $\mathbf{A}_{\text{outout}}(t)$ are the acceleration input to the accelerometer and the output from the target accelerometer, respectively. Normally, an accelerometer has sensitivity not only along the sensitivity axis but also along the axis that is orthogonal to the sensitivity axis. The sensitivity matrix of an accelerometer is defined as follows:

$$\mathbf{S} = \begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{pmatrix} \quad (\text{A.2})$$

where $S_{pq}(p=q)$ and $S_{pq}(p \neq q)$ are a normal sensitivity and a cross-sensitivity, respectively. Each element of the sensitivity matrix is a function of angular frequency, ω . $S_{xx}(j\omega)$, $S_{xy}(j\omega)$ and $S_{xz}(j\omega)$ are defined as follows by activating the target accelerometer using the acceleration $(a_x(t) \ 0 \ 0)$ along the X-axis:

$$\begin{pmatrix} S_{xx}(j\omega) \\ S_{yx}(j\omega) \\ S_{zx}(j\omega) \end{pmatrix} = \begin{pmatrix} \frac{L[a_{x,x}(t)]}{L[a_x(t)]} \\ \frac{L[a_{y,x}(t)]}{L[a_x(t)]} \\ \frac{L[a_{z,x}(t)]}{L[a_x(t)]} \end{pmatrix} \quad (\text{A.3})$$

where $a_{x,x}(t)$, $a_{y,x}(t)$ and $a_{z,x}(t)$ are the X-axis output by X-axis input, Y-axis output by X-axis input and Z-axis output by X-axis input, respectively, L stands for Laplace transform operator and j is the imaginary unit.

$S_{xy}(j\omega)$, $S_{yy}(j\omega)$ and $S_{zy}(j\omega)$ are defined as follows by activating the target accelerometer using acceleration $\begin{pmatrix} 0 & a_y(t) & 0 \end{pmatrix}$ along the Y-axis:

$$\begin{pmatrix} S_{xy}(j\omega) \\ S_{yy}(j\omega) \\ S_{zy}(j\omega) \end{pmatrix} = \begin{pmatrix} \frac{L[a_{x,y}(t)]}{L[a_y(t)]} \\ \frac{L[a_{y,y}(t)]}{L[a_y(t)]} \\ \frac{L[a_{z,y}(t)]}{L[a_y(t)]} \end{pmatrix} \quad (\text{A.4})$$

where $a_{x,y}(t)$, $a_{y,y}(t)$ and $a_{z,y}(t)$ are the X-axis output by Y-axis input, Y-axis output by Y-axis input and Z-axis output by Y-axis input, respectively.

$S_{xz}(j\omega)$, $S_{yz}(j\omega)$ and $S_{zz}(j\omega)$ are defined as follows by activating the target accelerometer using the acceleration $\begin{pmatrix} 0 & 0 & a_z(t) \end{pmatrix}$ along Z-axis:

$$\begin{pmatrix} S_{xz}(j\omega) \\ S_{yz}(j\omega) \\ S_{zz}(j\omega) \end{pmatrix} = \begin{pmatrix} \frac{L[a_{x,z}(t)]}{L[a_z(t)]} \\ \frac{L[a_{y,z}(t)]}{L[a_z(t)]} \\ \frac{L[a_{z,z}(t)]}{L[a_z(t)]} \end{pmatrix} \quad (\text{A.5})$$

where $a_{x,z}(t)$, $a_{y,z}(t)$ and $a_{z,z}(t)$ are the X-axis output by Z-axis input, Y-axis output by Z-axis input and Z-axis output by Z-axis input, respectively.

Therefore, the general relationship between the input vector acceleration to the target accelerometer and the output from the accelerometer in the frequency domain is expressed as follows:

$$\begin{aligned} & L[\mathbf{A}_{\text{output}}] \\ &= \begin{pmatrix} L[a_{s,x}(t)] \\ L[a_{s,y}(t)] \\ L[a_{s,z}(t)] \end{pmatrix} = \begin{pmatrix} a_{s,x}(j\omega) \\ a_{s,y}(j\omega) \\ a_{s,z}(j\omega) \end{pmatrix} \\ &= \begin{pmatrix} S_{xx}(j\omega) & S_{xy}(j\omega) & S_{xz}(j\omega) \\ S_{yx}(j\omega) & S_{yy}(j\omega) & S_{yz}(j\omega) \\ S_{zx}(j\omega) & S_{zy}(j\omega) & S_{zz}(j\omega) \end{pmatrix} \begin{pmatrix} a_{g,x}(j\omega) \\ a_{g,y}(j\omega) \\ a_{g,z}(j\omega) \end{pmatrix} \end{aligned} \quad (\text{A.6})$$

A.2.1.2 Sensitivity matrix of two-axis accelerometer

Even when the target accelerometer is two-axis type, the exact definition still needs to be shown in a matrix form. If the target accelerometer is installed in the X-Y plane, components of the sensitivity matrix related to the Z-axis output such as $S_{zx}(j\omega)$, $S_{zy}(j\omega)$ and $S_{zz}(j\omega)$ are of course zero. However, the output induced by the X-axis input and Y-axis input acceleration can be influenced by the Z-axis acceleration input as well. The following relationship therefore holds:

$$\begin{aligned}
 L[A_{\text{output}}(t)] &= \begin{pmatrix} L[a_{s,x}(t)] \\ L[a_{s,y}(t)] \end{pmatrix} = \begin{pmatrix} a_{s,x}(j\omega) \\ a_{s,y}(j\omega) \end{pmatrix} \\
 &= \begin{pmatrix} S_{xx}(j\omega) & S_{xy}(j\omega) & S_{xz}(j\omega) \\ S_{yx}(j\omega) & S_{yy}(j\omega) & S_{yz}(j\omega) \end{pmatrix} \begin{pmatrix} a_{g,x}(j\omega) \\ a_{g,y}(j\omega) \\ a_{g,z}(j\omega) \end{pmatrix}
 \end{aligned} \tag{A.7}$$

where j is the imaginary unit.

A.2.1.3 Sensitivity matrix of one-axis accelerometer

If the target accelerometer is one-axis type, it should be accepted that the exact definition shall be given in a matrix form. Here it is assumed that the accelerometer sensitivity axis is equal to the X-axis.

$$\begin{aligned}
 L[A_{\text{output}}(t)] &= L[a_{s,x}(t)] = a_{s,x}(j\omega) \\
 &= \begin{pmatrix} S_{xx}(j\omega) & S_{xy}(j\omega) & S_{xz}(j\omega) \\ S_{yx}(j\omega) & S_{yy}(j\omega) & S_{yz}(j\omega) \end{pmatrix} \begin{pmatrix} a_{g,x}(j\omega) \\ a_{g,y}(j\omega) \\ a_{g,z}(j\omega) \end{pmatrix}
 \end{aligned} \tag{A.8}$$

A.2.2 Calibration

A.2.2.1 Calibration using a vibration table

A.2.2.1.1 Calibration using a three-dimensional vibration table

Mathematical consideration has shown that a matrix should express the sensitivity of an accelerometer. Calibration is a process of determining all of the components of the matrix as a function of frequency and other parameters, if necessary. Since acceleration is a vector quantity, an accelerometer shall be calibrated not only by the amplitude but also the direction on principle. Calibration of the accelerometer which measures acceleration as a vector must inspect if the component of acceleration along the sensitivity axis is accurately measured, regardless of the direction. It is, needless to say, impossible to check it in every direction. However, determining every component in the sensitivity matrix is equivalent to calibrating both amplitude and direction, which is the essence of a vector quantity.

At the specified frequency f_i , three kinds of vector acceleration are generated:

$$\mathbf{a}_{i,1} = \begin{pmatrix} a_{i,1,x} e^{j2\pi f_i t} \\ a_{i,1,y} e^{j2\pi f_i t} \\ a_{i,1,z} e^{j2\pi f_i t} \end{pmatrix} \tag{A.9}$$

$$\mathbf{a}_{i,2} = \begin{pmatrix} a_{i,2,x} e^{j2\pi f_i t} \\ a_{i,2,y} e^{j2\pi f_i t} \\ a_{i,2,z} e^{j2\pi f_i t} \end{pmatrix} \tag{A.10}$$

$$\mathbf{a}_{i,3} = \begin{pmatrix} a_{i,3,x} e^{j2\pi f_i t} \\ a_{i,3,y} e^{j2\pi f_i t} \\ a_{i,3,z} e^{j2\pi f_i t} \end{pmatrix} \quad (\text{A.11})$$

Output vector acceleration from the target accelerometer $\mathbf{b}_{i,1}$, $\mathbf{b}_{i,2}$ and $\mathbf{b}_{i,3}$ are expressed as follows:

$$\begin{aligned} \mathbf{b}_{i,1} &= \begin{pmatrix} b_{i,1,x}(j\omega_i) e^{j2\pi f_i t} \\ b_{i,1,y}(j\omega_i) e^{j2\pi f_i t} \\ b_{i,1,z}(j\omega_i) e^{j2\pi f_i t} \end{pmatrix} \\ &= \begin{pmatrix} S_{xx}(j\omega_i) & S_{xy}(j\omega_i) & S_{xz}(j\omega_i) \\ S_{yx}(j\omega_i) & S_{yy}(j\omega_i) & S_{yz}(j\omega_i) \\ S_{zx}(j\omega_i) & S_{zy}(j\omega_i) & S_{zz}(j\omega_i) \end{pmatrix} \begin{pmatrix} a_{i,1,x} e^{j2\pi f_i t} \\ a_{i,1,y} e^{j2\pi f_i t} \\ a_{i,1,z} e^{j2\pi f_i t} \end{pmatrix} \end{aligned} \quad (\text{A.12})$$

$$\mathbf{b}_{i,2} = \begin{pmatrix} S_{xx}(j\omega_i) & S_{xy}(j\omega_i) & S_{xz}(j\omega_i) \\ S_{yx}(j\omega_i) & S_{yy}(j\omega_i) & S_{yz}(j\omega_i) \\ S_{zx}(j\omega_i) & S_{zy}(j\omega_i) & S_{zz}(j\omega_i) \end{pmatrix} \mathbf{a}_{i,2} \quad (\text{A.13})$$

$$\mathbf{b}_{i,3} = \begin{pmatrix} S_{xx}(j\omega_i) & S_{xy}(j\omega_i) & S_{xz}(j\omega_i) \\ S_{yx}(j\omega_i) & S_{yy}(j\omega_i) & S_{yz}(j\omega_i) \\ S_{zx}(j\omega_i) & S_{zy}(j\omega_i) & S_{zz}(j\omega_i) \end{pmatrix} \mathbf{a}_{i,3} \quad (\text{A.14})$$

where each component of $(\mathbf{b}_{i,1} \ \mathbf{b}_{i,2} \ \mathbf{b}_{i,3})$ is a complex number and should be measured with the maximum possible precision, i.e. laser interferometer. Solving following simultaneous linear equations will lead to the sensitivity matrix at a given frequency of f_i , ($\omega_i = 2\pi f_i$).

$$\begin{aligned} S_{xx}(j\omega_i) a_{i,1,x} + S_{xy}(j\omega_i) a_{i,1,y} + S_{xz}(j\omega_i) a_{i,1,z} &= b_{i,1,x}(j\omega_i) \\ S_{yx}(j\omega_i) a_{i,1,x} + S_{yy}(j\omega_i) a_{i,1,y} + S_{yz}(j\omega_i) a_{i,1,z} &= b_{i,1,y}(j\omega_i) \\ S_{zx}(j\omega_i) a_{i,1,x} + S_{zy}(j\omega_i) a_{i,1,y} + S_{zz}(j\omega_i) a_{i,1,z} &= b_{i,1,z}(j\omega_i) \\ S_{xx}(j\omega_i) a_{i,2,x} + S_{xy}(j\omega_i) a_{i,2,y} + S_{xz}(j\omega_i) a_{i,2,z} &= b_{i,2,x}(j\omega_i) \\ S_{yx}(j\omega_i) a_{i,2,x} + S_{yy}(j\omega_i) a_{i,2,y} + S_{yz}(j\omega_i) a_{i,2,z} &= b_{i,2,y}(j\omega_i) \\ S_{zx}(j\omega_i) a_{i,2,x} + S_{zy}(j\omega_i) a_{i,2,y} + S_{zz}(j\omega_i) a_{i,2,z} &= b_{i,2,z}(j\omega_i) \\ S_{xx}(j\omega_i) a_{i,3,x} + S_{xy}(j\omega_i) a_{i,3,y} + S_{xz}(j\omega_i) a_{i,3,z} &= b_{i,3,x}(j\omega_i) \\ S_{yx}(j\omega_i) a_{i,3,x} + S_{yy}(j\omega_i) a_{i,3,y} + S_{yz}(j\omega_i) a_{i,3,z} &= b_{i,3,y}(j\omega_i) \\ S_{zx}(j\omega_i) a_{i,3,x} + S_{zy}(j\omega_i) a_{i,3,y} + S_{zz}(j\omega_i) a_{i,3,z} &= b_{i,3,z}(j\omega_i) \end{aligned} \quad (\text{A.15})$$

Rewriting Equation (A.15) gives the Equation (A.16) as simultaneous linear equations on sensitivity matrix components:

$$\begin{pmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{pmatrix} \begin{pmatrix} S_{xx} \\ S_{xy} \\ S_{xz} \\ S_{yx} \\ S_{yy} \\ S_{yz} \\ S_{zx} \\ S_{zy} \\ S_{zz} \end{pmatrix} = \begin{pmatrix} b_{i,1,x} \\ b_{i,1,y} \\ b_{i,1,z} \\ b_{i,2,x} \\ b_{i,2,y} \\ b_{i,2,z} \\ b_{i,3,x} \\ b_{i,3,y} \\ b_{i,3,z} \end{pmatrix} \quad (\text{A.16})$$

It should be noted that the right side of the Equations (A.16) is a complex vector. The relation obtained by exchanging rows of the coefficient matrix as shown in Expression (A.17) demonstrates that the Equations (A.16) can be solved if $a_{i,1}$, $a_{i,2}$ and $a_{i,3}$ are linearly independent.

$$\begin{vmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{vmatrix} = - \begin{vmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{vmatrix}^3 \quad (\text{A.17})$$

The frequency response diagram requires repeated measurement at frequency f_n ($n = 1, \dots, N$) and solving the above simultaneous linear equations.

If the target accelerometer is two-axis type, the following equations shall be solved to obtain all of the components of the sensitivity matrix at any given frequency, f_i .

$$\begin{aligned} S_{xx}(j\omega_i)a_{i,1,x} + S_{xy}(j\omega_i)a_{i,1,y} + S_{xz}(j\omega_i)a_{i,1,z} &= b_{i,1,x} \\ S_{yx}(j\omega_i)a_{i,1,x} + S_{yy}(j\omega_i)a_{i,1,y} + S_{yz}(j\omega_i)a_{i,1,z} &= b_{i,1,y} \\ S_{xx}(j\omega_i)a_{i,2,x} + S_{xy}(j\omega_i)a_{i,2,y} + S_{xz}(j\omega_i)a_{i,2,z} &= b_{i,2,x} \\ S_{yx}(j\omega_i)a_{i,2,x} + S_{yy}(j\omega_i)a_{i,2,y} + S_{yz}(j\omega_i)a_{i,2,z} &= b_{i,2,y} \\ S_{xx}(j\omega_i)a_{i,3,x} + S_{xy}(j\omega_i)a_{i,3,y} + S_{xz}(j\omega_i)a_{i,3,z} &= b_{i,3,x} \\ S_{yx}(j\omega_i)a_{i,3,x} + S_{yy}(j\omega_i)a_{i,3,y} + S_{yz}(j\omega_i)a_{i,3,z} &= b_{i,3,z} \end{aligned} \quad (\text{A.18})$$

Rewriting the Equations (A.18) gives the Equations (A.19) as simultaneous linear equations on sensitivity matrix components.

$$\begin{pmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{pmatrix} \begin{pmatrix} S_{xx}(j\omega_i) \\ S_{xy}(j\omega_i) \\ S_{xz}(j\omega_i) \\ S_{yx}(j\omega_i) \\ S_{yy}(j\omega_i) \\ S_{yz}(j\omega_i) \end{pmatrix} = \begin{pmatrix} b_{i,1,x} \\ b_{i,1,y} \\ b_{i,2,x} \\ b_{i,2,y} \\ b_{i,3,x} \\ b_{i,3,y} \end{pmatrix} \quad (\text{A.19})$$

It should be noted that the right side of the Equations (A.19) is a complex vector. The relation obtained by exchanging the rows of the coefficient matrix demonstrates that the Equations (A.19) can be solved if $a_{i,1}$, $a_{i,2}$ and $a_{i,3}$ are linearly independent as shown in the Expression (A.20).

$$\begin{vmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} & 0 & 0 & 0 \\ 0 & 0 & 0 & a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{vmatrix} = - \begin{vmatrix} a_{i,1,x} & a_{i,1,y} & a_{i,1,z} \\ a_{i,2,x} & a_{i,2,y} & a_{i,2,z} \\ a_{i,3,x} & a_{i,3,y} & a_{i,3,z} \end{vmatrix}^2 \quad (\text{A.20})$$

If the target accelerometer is one-axis type, the following equations shall be solved to obtain all of the components in the sensitivity matrix at any given frequency, f_i .

$$\begin{aligned} S_{xx}(j\omega_i)a_{i,1,x} + S_{xy}(j\omega_i)a_{i,1,y} + S_{xz}(j\omega_i)a_{i,1,z} &= b_{i,1,x} \\ S_{xx}(j\omega_i)a_{i,2,x} + S_{xy}(j\omega_i)a_{i,2,y} + S_{xz}(j\omega_i)a_{i,2,z} &= b_{i,2,x} \\ S_{xx}(j\omega_i)a_{i,3,x} + S_{xy}(j\omega_i)a_{i,3,y} + S_{xz}(j\omega_i)a_{i,3,z} &= b_{i,3,x} \end{aligned} \quad (\text{A.21})$$

The simultaneous linear Equations (A.21) can be solved if $a_{i,1}$, $a_{i,2}$ and $a_{i,3}$ are linearly independent.

A.2.2.1.2 Calibration using a one-dimensional vibration table (see Table A.1)

The sensitivity matrix might be derived using a one-dimensional vibration tables in theory. The one-dimensional vibration table generates either one-dimensional translational motion or rotational motion. However, following difficulties should be considered seriously:

- The influence of the gravitational acceleration on the performance of the mechanical part of the accelerometer is neglected.
- The base strain of the target accelerometer caused by the installation is not constant, because mounting is adjusted so that the motion direction of the one-dimensional table may be along with one of the input axis of the multi-axis accelerometers.
- Low calibration efficiency is unavoidable.
- High calibration cost is introduced because of the low calibration efficiency.
- It is difficult to cope with the high volume production of semiconductor accelerometers.
- Information of the jig with precise adjustment and mechanical robustness is not available.

Figure A.1 gives an example of direction cosine.

Table A.1 – Symbols for the relationship between input acceleration and the output signal from an accelerometer using one-dimensional vibration table

Input side				Output side	
Excitation	Output acceleration of one-dimensional vibration table	Direction cosine between the input acceleration by one-dimensional vibration table and the input co-ordinate axis	Input acceleration vector	No. of axis	Output from the accelerometer
1	$a_{iz,1} \exp(j\omega t)$	$\cos \alpha_1$	$a_{iz,1} \begin{pmatrix} \cos \alpha_1 \\ \cos \beta_1 \\ \cos \gamma_1 \end{pmatrix} \exp(j\omega t)$	1	$V_{ox1} \exp(j\omega t)$
		$\cos \beta_1$		2	$(V_{ox1} \ V_{oy1}) \exp(j\omega t)$
		$\cos \gamma_1$		3	$(V_{ox1} \ V_{oy1} \ V_{oz1}) \exp(j\omega t)$
2	$a_{iz,2} \exp(j\omega t)$	$\cos \alpha_2$	$a_{iz,2} \begin{pmatrix} \cos \alpha_2 \\ \cos \beta_2 \\ \cos \gamma_2 \end{pmatrix} \exp(j\omega t)$	1	$V_{ox2} \exp(j\omega t)$
		$\cos \beta_2$		2	$(V_{ox2} \ V_{oy2}) \exp(j\omega t)$
		$\cos \gamma_2$		3	$(V_{ox2} \ V_{oy2} \ V_{oz2}) \exp(j\omega t)$
3	$a_{iz,3} \exp(j\omega t)$	$\cos \alpha_3$	$a_{iz,3} \begin{pmatrix} \cos \alpha_3 \\ \cos \beta_3 \\ \cos \gamma_3 \end{pmatrix} \exp(j\omega t)$	1	$V_{ox3} \exp(j\omega t)$
		$\cos \beta_3$		2	$(V_{ox3} \ V_{oy3}) \exp(j\omega t)$
		$\cos \gamma_3$		3	$(V_{ox3} \ V_{oy3} \ V_{oz3}) \exp(j\omega t)$

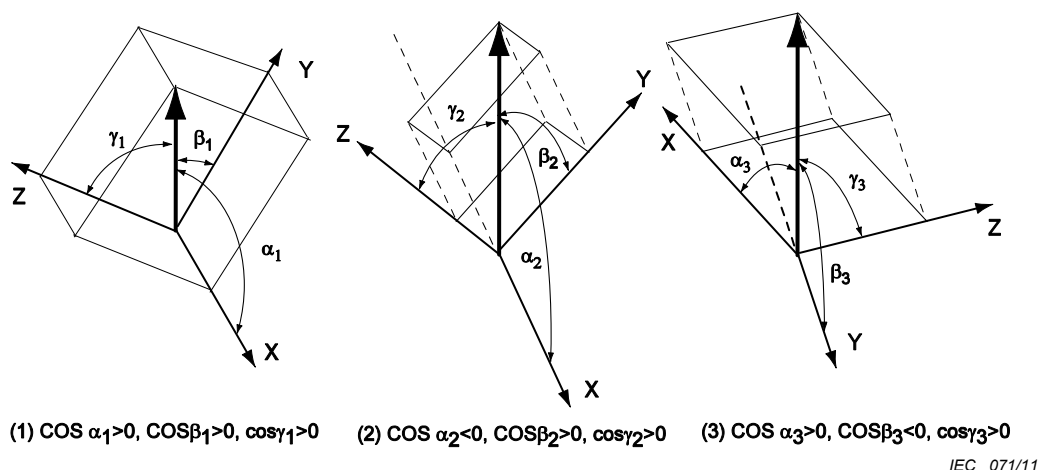


Figure A.1 – Example of direction cosine

A.2.2.2 Calibration using the impact excitation

A.2.2.2.1 Calibration using a three-dimensional impact exciter

The apparatus of motion generation for calibration is originally a motion simulator of the real motion vector space. If the target accelerometer is used to measure the acceleration in the three-dimensional motion vector space, it is natural to think that the motion generator i.e. the vibration table, should generate the three-dimensional motion vector space. The acceleration vector $\mathbf{a}$ generated by an N -dimensional vibration table is described by the following expression:

$$\mathbf{a} = \sum_{j=1}^N c_j \mathbf{e}_j \quad (\text{A.22})$$

where $c_j (j=1, \dots, N)$ are the constants and $\mathbf{e}_j (j=1, \dots, N)$ are the unit acceleration vector generated by each actuator in total up to N . It should be noted that the N -dimensional vibration table could generate the arbitrary acceleration as the linear combination expressed by Expression (A.22). On the other hand, an N -axis vibration table could not normally generate arbitrary acceleration in the form of Expression (A.22).

Table A.2 – Symbols for input acceleration and output signals from an accelerometer

Excitation	Input acceleration as a function of time	Number of axis	Output acceleration signal
1st	$(a_{i,1,x}(t) \ a_{i,1,y}(t) \ a_{i,1,z}(t))$	1	$a_{oz1}(t)$
		2	$(a_{oy1}(t) \ a_{oz1}(t))$
		3	$(a_{ox1}(t) \ a_{oy1}(t) \ a_{oz1}(t))$
2nd	$(a_{i,2,x}(t) \ a_{i,2,y}(t) \ a_{i,2,z}(t))$	1	$a_{oz2}(t)$
		2	$(a_{oy2}(t) \ a_{oz2}(t))$
		3	$(a_{ox2}(t) \ a_{oy2}(t) \ a_{oz2}(t))$
3rd	$(a_{i,3,x}(t) \ a_{i,3,y}(t) \ a_{i,3,z}(t))$	1	$a_{oz3}(t)$
		2	$(a_{oy3}(t) \ a_{oz3}(t))$
		3	$(a_{ox3}(t) \ a_{oy3}(t) \ a_{oz3}(t))$

Table A.3 – Definition of symbols for describing the input acceleration, output signal from the target accelerometer and the direction cosine repeated three times

Excitation acceleration		Relation along the x-axis of the target accelerometer		Relation along the y-axis of the target accelerometer		Relation along the z-axis of the target accelerometer	
Excitation	Amplitude m/s ²	Output	Direction cosine	Output	Direction cosine	Output	Direction cosine
First time	$a_{i1}(t)$	$a_{ox1}(t)$	$\cos \alpha_1$	$a_{oy1}(t)$	$\cos \beta_1$	$a_{oz1}(t)$	$\cos \gamma_1$
Second time	$a_{i2}(t)$	$a_{ox2}(t)$	$\cos \alpha_2$	$a_{oy2}(t)$	$\cos \beta_2$	$a_{oz2}(t)$	$\cos \gamma_2$
Third time	$a_{i3}(t)$	$a_{ox3}(t)$	$\cos \alpha_3$	$a_{oy3}(t)$	$\cos \beta_3$	$a_{oz3}(t)$	$\cos \gamma_3$

The vector expression of the first time excitation, the second time excitation and the thirteenth time excitation are written as $(a_{ix1}(t) \ a_{iy1}(t) \ a_{iz1}(t))$, $(a_{ix2}(t) \ a_{iy2}(t) \ a_{iz2}(t))$ and $(a_{ix3}(t) \ a_{iy3}(t) \ a_{iz3}(t))$, respectively. Then the following definitions from definition (A.23) to definition (A.34) hold:

$$a_{i1}(t) = \sqrt{(a_{ix1}(t))^2 + (a_{iy1}(t))^2 + (a_{iz1}(t))^2} \quad (\text{A.23})$$

$$\cos \alpha_1 = \frac{a_{i1x}(t)}{a_{i1}(t)} \quad (\text{A.24})$$

$$\cos \beta_1 = \frac{a_{i1y}(t)}{a_{i1}(t)} \quad (\text{A.25})$$

$$\cos \gamma_1 = \frac{a_{i1z}(t)}{a_{i1}(t)} \quad (\text{A.26})$$

$$a_{i2}(t) = \sqrt{(a_{i2x}(t))^2 + (a_{i2y}(t))^2 + (a_{i2z}(t))^2} \quad (\text{A.27})$$

$$\cos \alpha_2 = \frac{a_{i2x}(t)}{a_{i2}(t)} \quad (\text{A.28})$$

$$\cos \beta_2 = \frac{a_{i2y}(t)}{a_{i2}(t)} \quad (\text{A.29})$$

$$\cos \gamma_2 = \frac{a_{i2z}(t)}{a_{i2}(t)} \quad (\text{A.30})$$

$$a_{i3}(t) = \sqrt{(a_{i3x}(t))^2 + (a_{i3y}(t))^2 + (a_{i3z}(t))^2} \quad (\text{A.31})$$

$$\cos \alpha_3 = \frac{a_{i3x}(t)}{a_{i3}(t)} \quad (\text{A.32})$$

$$\cos \beta_3 = \frac{a_{i3y}(t)}{a_{i3}(t)} \quad (\text{A.33})$$

$$\cos \gamma_3 = \frac{a_{i3z}(t)}{a_{i3}(t)} \quad (\text{A.34})$$

A.2.2.2.1.1 One-axis accelerometers

One-axis level 1 accelerometers are calibrated using the equipment in which the sensitivity axis of the target accelerometer coincides with the direction of the impact acceleration. In the frequency and time domain in which the dynamic linearity is guaranteed, normal sensitivity is derived from the transfer function, $G_N(S)$ formulated by Definition (A.35).

$$G_N(S) = \frac{L[V_{\text{out}}(t)]}{L[a_{\text{in}}(t)]} \quad (\text{A.35})$$

where $a_{\text{in}}(t)$ and $V_{\text{out}}(t)$ are the input acceleration and the output from the accelerometer, respectively. The cross-sensitivity is also obtained from the transfer function that is derived using the set-up in which the impact acceleration is in the plane, perpendicular to the normal sensitivity of the target accelerometer.