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Fine ceramics (advanced ceramics, advanced technical ceramics) — Method for measuring the power generation characteristics of piezoelectric resonant devices for stand-alone power sources

Céramiques techniques — Méthode de mesurage des caractéristiques de production d'énergie électrique d'un dispositif résonnant piézoélectrique pour une source d'alimentation autonome

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Foreword

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This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

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

Introduction

Economic development is supported by infrastructure such as roads and railroads; however, maintaining ageing infrastructure at a low cost is a problem. An effective monitoring system for maintaining the health of infrastructure at a low cost is necessary, therefore a stand-alone power source is required because of requirements such as installation location, number of items and period of use. In addition, in the internet of things (IoT), power is needed everywhere in order for everything to be connected to the internet, and from that perspective a stand-alone power source is expected.

A self-supporting power source is a technology that collects energy such as light, vibration and heat, converts it into electrical energy and uses it. Power supplies for small electronic devices include those for various mobile devices, lighting switches, automotive tire-pressure monitoring systems (TPMS) and wireless sensor networks (sensor power supplies) that monitor infrastructure and the environment. The use of such power supplies is expanding to active type tags used for recognition, such as radio frequency identifiers (RFIDs). Vibratory electrical conversion using vibrational energy is considered to be easy to use because of its high energy density after sunlight. Various power generation experiments have already been conducted and its practical application has been accelerated. There are methods that use piezoelectric devices and electromagnetic induction for vibration electric conversion, but methods using ceramic piezoelectric devices are prominent because of the output voltage, device size and degree of structural freedom. The vibrations used in power generation in daily life have a wide variety of frequencies, and it is difficult to set conditions for obtaining an appropriate amount of power generation with piezoelectric devices that are highly frequency-dependent. Piezoelectric device structures are also broadly divided into cantilever (beam), plate and double-supported beam shapes, and the sizes are diversified according to the purpose and application. It is also difficult to set conditions.

Currently, the measurement of power generation performance of piezoelectric devices for self-supporting power supplies is performed by an arbitrary method. What device structure (e.g. size, structure) will be used? What kind of vibration (e.g. frequency, additional mass, displacement) is applied to the piezoelectric body? What kind of circuit configuration (e.g. output voltage, current, conversion efficiency, measuring instrument) is standardized?

For this reason, this document was created for measuring the power generation characteristics of piezoelectric devices for self-supporting power supplies.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Method for measuring the power generation characteristics of piezoelectric resonant devices for stand-alone power sources

1 Scope

This document specifies a method for measuring power generation characteristics to evaluate and determine the output power, mechanical quality factor, electromechanical coupling factor and output efficiency of piezoelectric resonant devices used for self-sustaining power sources.

This document defines vibration-based test methods and characteristic parameters in order to accurately and practically evaluate the performance of piezoelectric resonant devices.

2 Normative references

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

ISO 20507, *Fine ceramics (advanced ceramics, advanced technical ceramics) — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 20507 and the following apply.

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

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

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

3.1
resonance frequency
frequency when output voltage reaches maximum

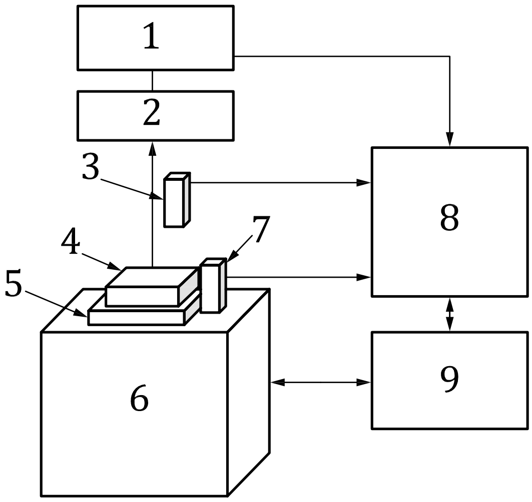
3.2
resonance peak width
difference in frequency between two points having a value of $1/\sqrt{2}$ of the maximum output voltage in an output voltage wave form

4 Measurement principle

A piezoelectric resonant device is subjected to mechanical vibration and the accompanying electrical charge generated by the piezoelectric resonant device is measured by load resistance as an output voltage, from which power generation characteristics are determined. The principal factors affecting power generation characteristics are the mechanical quality factor (Q_m) and the electromechanical coupling coefficient (k^2) of the piezoelectric device.

5 Apparatus

The equipment used for measurement and its configuration is as follows. Figure 1 shows a block diagram of the measuring system. Calibrated apparatus shall be used for measurement.



Key

1 voltmeter
2 load resistance
3 laser displacement meter
4 piezoelectric resonant device
5 mounting jig
6 vibration device
7 accelerometer
8 recorder
9 vibration controller

Figure 1 — Block diagram of measuring system

5.1 Voltmeter, connected to the load resistance to measure the output voltage of the piezoelectric resonant device. The input impedance of the voltmeter shall be at least ten times greater than the output impedance of the piezoelectric resonant device. If the input impedance is too low, the impedance should be converted at a stage prior to the voltmeter.

5.2 Load resistance, a resistance between the piezoelectric resonant device and the voltmeter used for measuring the output voltage of the piezoelectric resonant device.

5.3 Laser displacement meter, for measuring the displacement of an object using laser light. When an additional weight can be observed directly, a laser displacement meter is used to measure change in the position of the additional weight, which improves precision in the measurement of acceleration resulting from application of mechanical vibration. On this basis, installation of a laser displacement meter is acceptable. The frequency bandwidth shall be capable of handling the applied frequency of vibration.

5.4 Mounting jig, for mounting a piezoelectric resonant device to the vibration device. The mounting jig shall have no natural frequency in the measurement bandwidth. The natural frequency of the mounting jig shall be higher than the upper limit of the measurement frequency. The moment of the piezoelectric resonant device attributable to resonance shall be absorbable. See Clause A.3 for further information regarding the mounting jig.

5.5 Vibration device, which generates a mechanical vibration applied to the piezoelectric resonant device. The device shall be capable of sinusoidal output and of vibrational output at frequencies and accelerations in the ranges needed for measurement. The device should also have a feedback control function intended to prevent a decrease in applied vibrational acceleration when the piezoelectric resonant device has reached a resonant state. The vibrating device shall be provided with anti-vibration measures. The guideline for selecting the vibration device and mounting jig is shown in Clause A.2.

5.6 Accelerometer, which measures the acceleration of the mechanical vibration applied to the piezoelectric resonant device. Bandwidth shall be capable of handling the applied frequency of vibration. Attachment to the piezoelectric resonant device should reference A.2.3.

5.7 Recorder, which records vibration frequency, output voltage and acceleration continually. When an additional weight can be observed directly, the displacement of the additional weight is also recorded.

5.8 Vibration controller, which controls the action of the vibration resonant device to prevent noise and other such effects from changing the acceleration or frequency of applied vibration.

6 Piezoelectric resonant device

6.1 Piezoelectric resonant device configuration

The piezoelectric resonant device shall have a structure in which an additional weight is attached to the tip of a planar material to which piezoelectric material is attached. See Figure 2 and Figure 3.

a) The piezoelectric resonant device comprises piezoelectric material, which generates an electrical charge when subjected to a mechanical strain, planar material to which the piezoelectric material is attached and an electrode for extracting an output voltage. See Figure 2 and Figure 3.

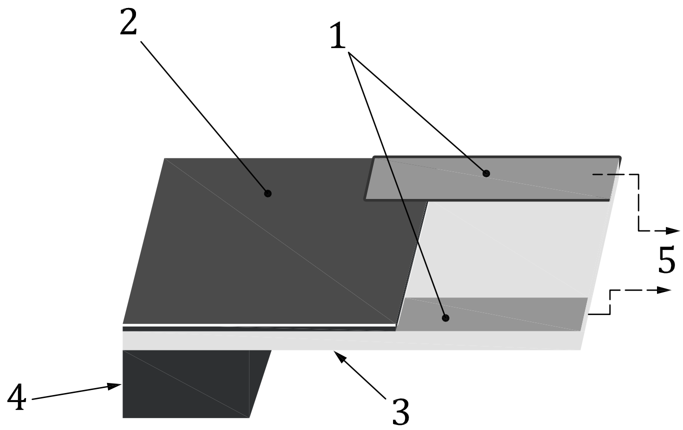
b) To obtain the output voltage efficiently, an additional weight which imparts acceleration to the piezoelectric resonant device shall be installed. The form of the additional weight is of no particular concern, provided that it does not affect vibration. The effective mass (*m*) of the additional weight in Formula (7) used to calculate theoretical output power is taken as the sum of the mass of the applied weight and the mass of the piezoelectric material during vibration.

c) The piezoelectric material shall be given a polarizing treatment in the orientation of its thickness.

d) The piezoelectric resonant device shall be fixed securely to the mounting jig with bolts or other such means. See Figure 3.

e) The lead wire to extract the output voltage shall have a hardness and mass unaffected by vibrational testing.

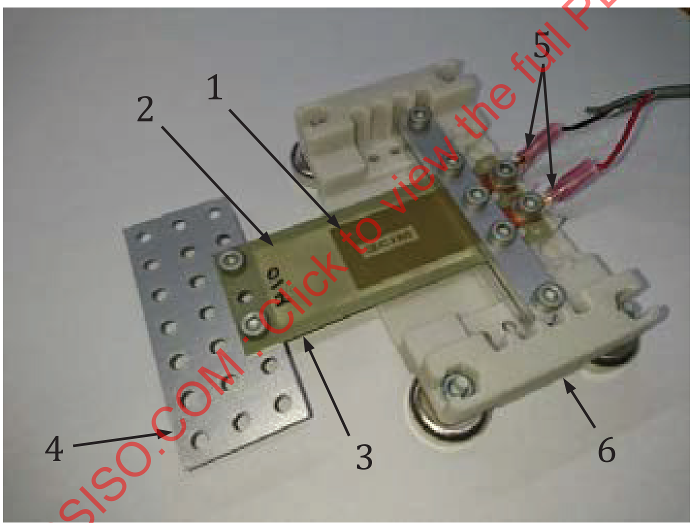
f) When a laser displacement meter is used, displacement of the piezoelectric resonant device should be measured as far toward its tip as possible. The surface for laser irradiation should also have a mirror finish to allow precise capture of reflected laser light.



Key

1 electrode
2 piezoelectric material
3 planar material
4 additional weight
5 lead wire

Figure 2 — Schematic of a piezoelectric resonant device



Key

1 electrode
2 piezoelectric material
3 planar material
4 additional weight
5 lead wire
6 mounting jig

Figure 3 — Example of a piezoelectric resonant device fixed with a mounting jig

6.2 Measurement of characteristic values

Before measuring the characteristic value, the length, width, thickness, mass and resonance frequency of the piezoelectric material forming the piezoelectric resonant device shall be measured. See Table B.1. Evaluation of piezoelectric properties is based on JEITA EM-4501A[1]. If an additional weight is attached, also measure its mass.

7 Output voltage measurement procedure and method for creating output voltage wave form

The output voltage measurement procedure and method for creating an output voltage wave form are as follows:

a) Set an applied vibrational acceleration, mechanical vibration frequency and load resistance. Use the vibration device to apply a sinusoidal, mechanical vibration to the piezoelectric resonant device and measure the output voltage generated by load resistance at both extremes.

b) Vary the frequency of the applied mechanical vibration back and forth at a constant rate between a lower-limit frequency and an upper-limit frequency set in a range of 0,9-fold to 1,1-fold centred on the resonance frequency before measurement of the piezoelectric resonant device. Keep the step width of the change in vibration frequency to 1/20 or lower versus the bandwidth of the piezoelectric resonant device. See Table B.2.

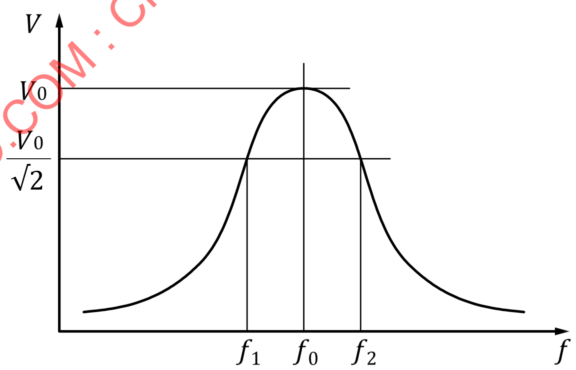
c) Apply the procedures in steps a) and b) with differing applied accelerations and differing mechanical vibration frequencies and load-resistance values. In a range between the minimum output of the vibration device and the rated input of the piezoelectric resonant device, vary the applied vibrational acceleration over three or more stages extending from 0,1-fold to fivefold versus the acting acceleration. In similar fashion, vary the load-resistance value over two orders of magnitude above and below a central value comprising the output impedance of the piezoelectric resonant device, and preferably over at least five stages including 0,01-fold, 0,1-fold, onefold, tenfold, a hundredfold and a thousandfold.

   EXAMPLE Resonance frequency (Hz): 38 to 43 (0,1 Hz step, 1-s hold).

   Applied vibrational acceleration (m/s^2): 0,1, 0,3 and 1,0.

   Load resistance (kΩ): 0,3, 1, 10, 30, 100, 1 000 and 10 000.

d) Create an output voltage wave form using the frequencies and the output voltages of the applied mechanical vibration (see Figure 4).



Key

f frequency

V output voltage

f_0 frequency at maximum output

f_1 frequency on low side when output voltage is $1/\sqrt{2}$ of maximum

f_2 frequency on high side when output voltage is $1/\sqrt{2}$ of maximum

V_0 maximum output voltage

Figure 4 — Example of output voltage wave form

e) If the output voltage wave form is not symmetrical (see Figure 5), check the piezoelectric resonant device and its mount for any problems and check connections with other equipment or similar issues. If problems are found, perform replacement, repair, adjustment or other necessary work. See A.2.1 for selection of a vibration device.

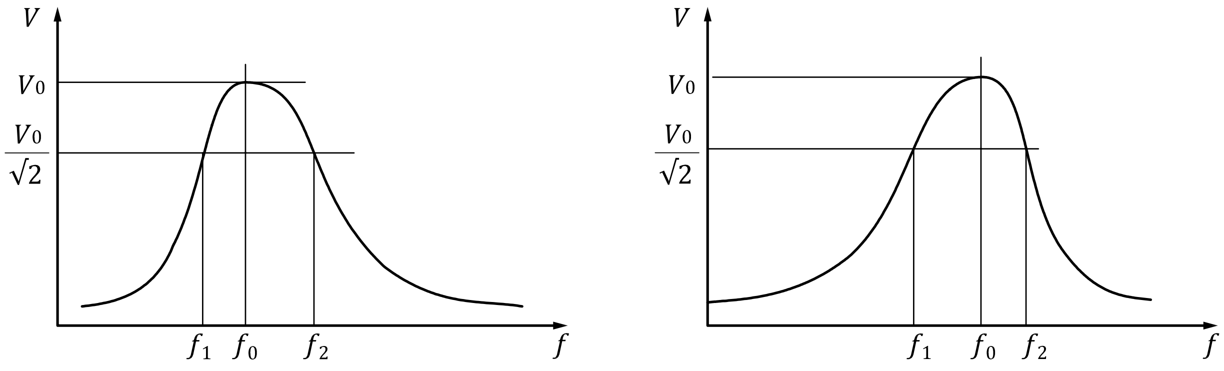


Figure 5 — Example of non-symmetrical output voltage wave form

f) Formula (1) represents a criterion for determining whether the output voltage wave form is symmetrical and shows an instance where left-right symmetry is within 10 % asymmetry on the low-frequency side. Formula (2) shows an instance where left-right symmetry is within 10 % asymmetry on the high-frequency side. However, this is not a sufficient condition in all cases and the wave form should be within the range specified by Formula (1) and Formula (2).

$$0{,}9 < \frac{f_0 - f_1}{f_2 - f_0} < 1 \tag{1}$$

$$1 < \frac{f_0 - f_1}{f_2 - f_0} < 1{,}1 \tag{2}$$

where

f_0 is the resonance frequency (Hz);

f_1 is the frequency on the low side when output voltage is $1/\sqrt{2}$ of maximum (Hz);

f_2 is the frequency on the high side when output voltage is $1/\sqrt{2}$ of maximum (Hz).

8 Calculation of characteristic values

8.1 General

Potential items for evaluation as factors affecting the power generation characteristics of the piezoelectric resonant device are: output power, mechanical quality factor (Q_m value), electromechanical coupling coefficient (k^2) and output efficiency (η).[2] The mass of the additional weight is a factor affecting power generation characteristics but is a design element, not an item for evaluation.

8.2 Output power

The output power of the piezoelectric resonant device is represented as power consumed by load resistance, as determined by Formula (3).

$$P_{out} = \frac{V_{out}^2}{R} \tag{3}$$

where

P_{out} is the output power (W);

V_{out} is the output voltage (V rms value);

R is the load resistance (Ω).

8.3 Mechanical quality factor

The mechanical quality factor of the piezoelectric resonant device is determined by Formula (4). $(f_2 - f_1)$ is also called the resonance peak width and is used for evaluation of Q_m.

$$Q_m = \frac{f_0}{f_2 - f_1} \tag{4}$$

where

Q_m is the mechanical quality factor;

f_0 is the resonance frequency (Hz);

f_1 is the frequency on the low side when output voltage is $1/\sqrt{2}$ of maximum (Hz);

f_2 is the frequency on the high side when output voltage is $1/\sqrt{2}$ of maximum (Hz).

8.4 Electromechanical coupling coefficient

The electromechanical coupling coefficient of the piezoelectric resonant device is determined by Formula (5).

$$k^2 = \frac{f_{oc}^2 - f_{sc}^2}{f_{sc}^2} \tag{5}$$

where

k^2 is the electromechanical coupling coefficient;

f_{sc} is the resonance frequency with minimum load resistance connected to piezoelectric device;

f_{oc} is the resonance frequency with maximum load resistance connected to piezoelectric device.

8.5 Output efficiency

The output efficiency of the piezoelectric resonant device is determined by Formula (6).

$$\eta = \frac{P_{max}}{P_{ave}} \times 100 \tag{6}$$

where

η is the output efficiency;

P_{max} is the maximum output power (W);

P_{ave} is the theoretical output power (W).

The maximum output power is taken as the measured maximum output power value obtained with the piezoelectric resonant device. Calculation of the theoretical output power follows Formula (7).

$$P_{\text{ave}} = \frac{mA^2 Q_{\text{m}}^*}{2\varpi_{\text{r}}\left(1+\sqrt{\left(1+\frac{1}{k^4 Q_{\text{m}}^{*2}}\right)}\right)} \tag{7}$$

where

P_{ave} is the theoretical output power (W);

m is the effective mass of additional weight (kg) summed with the mass of additional weight and the mass of piezoelectric unit during vibration;

A is the applied vibrational acceleration (m/s^2 rms value);

Q_{m}^* is the mechanical quality factor with connected load resistance of approximately 1/100 load resistance when maximum generated power is obtained (Q_{m});

ω_{r} is the angular frequency at maximum power generation (Rad/s);

k^2 is the electromechanical coupling coefficient.

9 Expression of principal constants in characteristic values

Express values of measured results and analytical results as follows. See Table B.3.

a) Obtain thickness, mass, resonance frequency before measurement, effective mass of additional weight, frequency sweep rate and resonance frequency and calculate output power, electromechanical coupling coefficient, maximum output power and theoretical output power to two decimal places by rounding off at the third decimal place.

b) Obtain length, width and mechanical quality factor to integers by rounding off at the first decimal place.

c) Obtain applied vibrational acceleration to one decimal place by rounding off at the second decimal place.

d) Obtain output voltage to three decimal places by rounding off at the fourth decimal place.

10 Test report

The test report shall contain the following information:

a) a reference to this document, i.e. ISO 5712:2022;

b) date of measurement and measurement personnel;

c) name, dimensions, mass of piezoelectric resonant device, resonance frequency before measurement and mass of additional weight as determined in Clause 6.2 (see Table B.1);

d) manufacturer and model number of vibration device, voltmeter and accelerometer;

e) when used, manufacturer and model of piezoelectric resonant device and number of laser displacement meter;

f) measurement parameters (vibrational frequency range, frequency sweep rate, applied vibrational acceleration range and load-resistance range) as determined in Clause 7 (see Table B.2);

g) measurement results (applied vibrational acceleration, load resistance, resonance frequency, output voltage, resonance peak width and output power) as determined in Clause 8 (see Tables B.2 and B.3);

h) analytical results (mechanical quality factor, electromechanical coupling coefficient, output power, applied vibrational acceleration, load resistance, theoretical output power and output efficiency) as determined in Clause 8 (see Tables B.3 and B.4);

i) temperature and humidity of measurement environment (at least at the start and end of measurement);

j) measurement-related comments (e.g. shape of mounting jig, method for securing piezoelectric device to vibration device);

k) deviations from the specified procedures, if any;

l) any unusual features observed.

Annex A
(informative)

Guidelines for selection of vibration device and mounting jig

A.1 General

This annex presents selection guidelines for performing reliable measurement with a vibration device and a mounting jig.

A.2 Vibration device

A.2.1 Device selection

The vibration device used should be an electromotive testing device which provides good wave form distortion starting at a low level of acceleration.

A.2.2 Vibrational force

The vibration device should have a rated vibrational force equal to or greater than the required vibrational force, as determined by Formula (A.1).

$$F = q \times (m_a + m_b + m) \times Q_{max} \times A_{max} \times \sqrt{2} \quad \text{(A.1)}$$

where

F	is the required vibrational force (N);
q	is the margin, typically 2 or greater;
m_a	is the mass of moving parts in the vibrator (kg);
m_b	is the total mass of the piezoelectric device and mounting jig (kg);
m	is the mass of weight (kg);
A_{max}	is the applied maximum vibrational acceleration (rms value, m/s^2);
Q_{max}	is the sample resonance factor (if unknown, 100 suggested).

NOTE Because the rated vibrational force of the vibration testing device is defined by its zero-peak force (0-P value), the conversion constant $\sqrt{2}$ is used to convert the effective value indicating the mean magnitude of vibration within a given duration (rms value) to a 0-P value.

A.2.3 Acceleration

The vibration device should have a rated device acceleration equal to or greater than the acceleration needed, as determined by Formula (A.2).

$$V = \frac{\sqrt{2} \times q \times A_{max}}{2\pi \times f_{min}} \quad \text{(A.2)}$$

where

V is the required acceleration (m/s);

q is the margin, typically 2;

A_{max} is the applied maximum vibrational acceleration (rms value, m/s^2);

f_{min} is the applied lower limit vibration frequency (Hz).

NOTE Because the rated acceleration of the vibration testing device is defined by its zero-peak force (0-P value), the conversion constant √2 is used to convert an effective value (rms value) to a 0-P value.

A.2.4 Displacement and carried mass

To account for a reduction in the range of motion of the vibrational device due to the mass of the mounting jig, the reduced rated displacement of the vibrational device as determined by Formula (A.3) should be equal to or greater than the required displacement, as determined by Formula (A.4).

$$D = \frac{2\sqrt{2} \times q \times A_{max}^2}{(2\pi f_{min})^2} \tag{A.3}$$

where

D is the required displacement (mm P-P);

q is the margin, typically 2;

A_{max} is the applied maximum vibrational acceleration (rms value, m/s^2);

f_{min} is the applied lower limit vibration frequency (Hz).

NOTE The constant 2 is used to convert a zero-peak value (0-P value) to a peak-peak value (P-P value), and the conversion constant √2 is used to convert an effective value (rms value) to a 0-P value.

$$D_m = 2 \times \left(\frac{D_s}{2} - \frac{m_b \times g}{K} \right) \tag{A.4}$$

where

D_m is the reduced rated displacement (mm P-P);

D_s is the device rated displacement (mm P-P);

K is the spring constant (N/mm);

m_b is the total mass of piezoelectric device and mounting jig (kg);

g is the gravitational acceleration 9,807 (m/s^2).

NOTE Compact vibration generators providing a vibrational force of 300 N or less frequently do not have a neutral point hold function for the moving portion, which is simply suspended by a spring. In such instances, the spring is compressed by the carried mass of the mounting jig and other components and the displacement that vibration can provide is reduced.

A.2.5 Isolation

The device should isolate to a level at or below approximately one third of the applied lower limit frequency. Particularly when a laser displacement meter is used for measurement, reaction from the vibration device should not be transmitted to ground.