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Fine ceramics (advanced ceramics, advanced technical ceramics) — Characteristic of piezoelectric properties under high-load conditions —

Part 2: Electrical transient response method under high vibration levels

Céramiques techniques (céramiques avancées, céramiques techniques avancées) — Caractéristique des propriétés piézoélectriques en conditions de charge élevée —

Partie 2: Méthode de la réponse transitoire électrique sous des niveaux vibratoires élevés

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Foreword

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

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

A list of all parts in the ISO 21819 series can be found on the ISO website.

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.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Characteristic of piezoelectric properties under high-load conditions —

Part 2: Electrical transient response method under high vibration levels

1 Scope

This document specifies a method of measuring piezoelectric properties of piezoelectric fine ceramics and other piezoelectric devices. It applies to electrical transient response methods for evaluating the piezoelectric properties of piezoelectric fine ceramics resonators under high vibration levels.

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 terminological databases for use in standardization at the following addresses:

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

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

3.1
electrical transient response method
method in which a voltage close to the resonance frequency is applied to a piezoelectric fine ceramic resonator, and a large amplitude state is realized by driving only for a brief time until vibration is excited, before characteristics of piezoelectric properties under an arbitrary vibration level are evaluated by using the attenuation waveform of vibration velocity and the current under short circuit of the electrical terminal

Note 1 to entry: Superior ability to exclude the effects of external electrical fields and temperature allows measurement and evaluation of characteristics in a vibrational stress load environment excluding these factors.

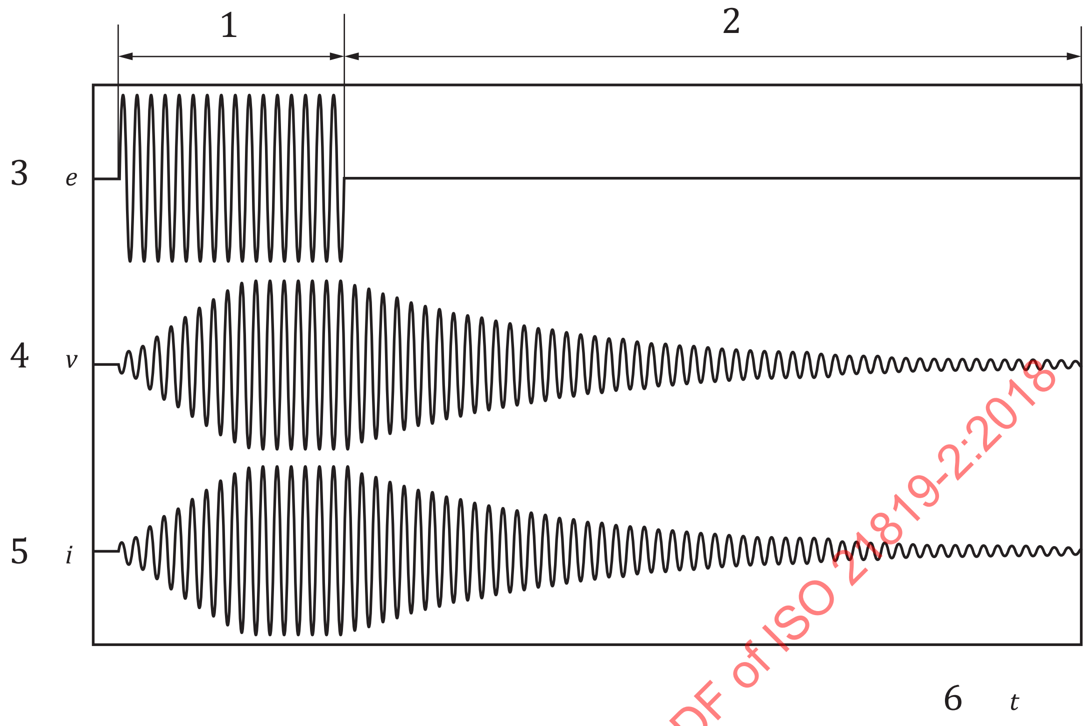
3.2
burst
driving for only a brief duration to excite vibration

4 Symbols

A	Force factor (N/V)
d_{31}	Equivalent piezoelectric constant (C/N)
f_{ri}	Resonance frequency of current (Hz)
f_{rv}	Resonance frequency of vibration velocity (Hz)
f_{rv1}	Instantaneous frequency of vibration velocity (Hz)
i	Current (A)
I_1	Instantaneous amplitude of current (A)
I_0	Amplitude of current (A)
M	Mass of test piece determined in 7.2 (kg)
$Q_{\mathrm{m}}{}^*$	Equivalent mechanical quality factor
$s_{11}{}^{\mathrm{E}*}$	Equivalent elastic compliance(m^2/N)
t	Time (s)
$T_{\mathrm{m}}{}^*$	Amplitude of equivalent maximum stress on central region of test piece (Pa)
v	Vibration velocity (m/s)
V_0	Amplitude of vibration velocity (m/s)
V_1	Instantaneous amplitude of vibration velocity (m/s)
X	Width of test piece (m)
Y	Length of test piece (m)
β_{i}	Decay constant of current (S^{-1})
β_{v}	Decay constant of vibration velocity (S^{-1})
β_{v1}	Instantaneous decay constant of vibration velocity (S^{-1})
ϕ_{i}	Initial phase of current
Φ_{v}	Initial phase of vibration velocity
ρ	Density determined in 7.2 (kg/m^3)

5 Principle

A voltage e near the resonance frequency of a piezoelectric fine ceramic resonator is applied to driving voltage then reduced to 0, placing the electrical terminals in a shorted state (e = 0, see Figure 1).



Key

1 burst drive
2 short circuited
3 voltage
4 vibration velocity
5 current
6 time

Figure 1 — Waveform of vibration velocity and current during burst voltage driving of a piezoelectric fine ceramic resonator

The decay waveforms of vibration velocity v and current i when electrical terminals are shorted (e = 0) after burst driving decay with a mechanical resonance frequency are shown in Formula (1) and Formula (2) (see Figure 1).

$$v = V_0 \varepsilon^{-\beta_\mathrm{v} t} \sin(2\pi f_\mathrm{rv} t + \varphi_\mathrm{v}) \tag{1}$$

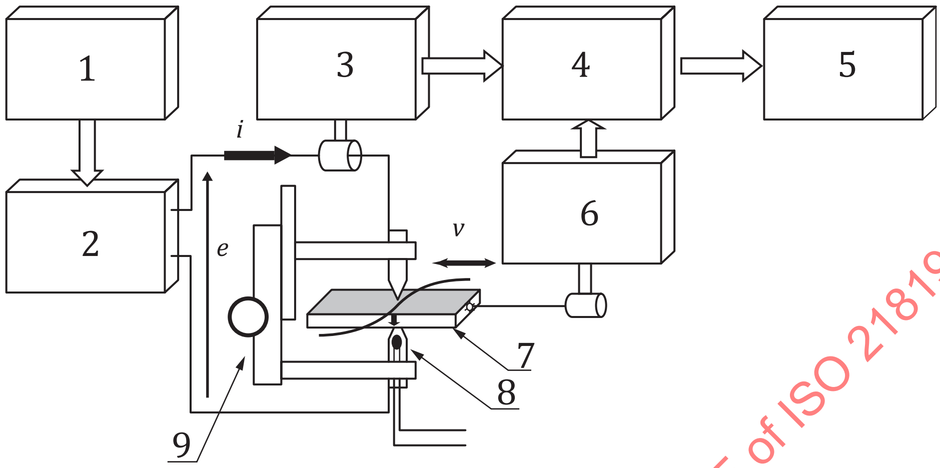
$$i = I_0 \varepsilon^{-\beta_\mathrm{i} t} \sin(2\pi f_\mathrm{ri} t + \varphi_\mathrm{i}) \tag{2}$$

β_v and β_i, and likewise f_rv and f_ri, can be taken as nearly the same values, but considering that this is a measurement analysis concerning mechanical vibration level, β_v is used as a decay constant and f_rv is used as a resonance frequency. In a large amplitude range, various other factors can also produce other frequency components. Consequently, only a first (fundamental) resonance frequency component is extracted from the decay waveform of the vibration velocity and the current when electrical terminals are shorted; the amplitude of the vibration velocity V_1, the amplitude of current I_1, resonance frequency f_rv1 and decay constant β_v1 in a selected schedule are measured and calculated, and these values are used to calculate the required constants at a selected vibration velocity. A voltage is applied only for a brief duration, and it then drops to 0 V, meaning that the electrical field applied to elements after electrical terminals are shorted and is also deemed zero, and since driving is only for a brief duration, measurements can be made under conditions where temperature change attributable to vibration loss is negligible, and piezoelectric characteristics can be evaluated in a vibrational stress load environment free from the effects of external electrical fields and temperature[1–10].

6 Measurement equipment

6.1 General

This clause details the apparatus used for measurement. Figure 2 also presents a simplified schematic of the measurement apparatus. A calibrated apparatus is used in measurement.



Key

1 function generator
2 power amplifier
3 current probe
4 digital storage oscilloscope
5 numerical analysis software
6 vibration velocity meter
7 test piece
8 thermocouple
9 test piece holder

Figure 2 — Simplified schematic of measurement apparatus

6.2 Function generator

The function generator shall output a sine wave greater than the first (fundamental) resonance frequency of the piezoelectric fine ceramic resonator, and allow the setting of its drive duration (burst driving).

6.3 Power amplifier

The power amplifier shall be capable of providing power amplification for sine waves at least two times greater than the first (fundamental) resonance frequency of a piezoelectric fine ceramic resonator, as well as four-quadrant output. The power amplifier should provide peak amplitudes of 200 V or more and 1 A or more for output voltage and current, respectively, and output impedance should be 0,5 Ω or less.

6.4 Vibration velocity meter

The vibration velocity meter shall be capable of measurement in a frequency range up to roughly five times the first (fundamental) resonance frequency of a piezoelectric fine ceramic resonator, in a vibration velocity range of approximately 0,01 m/s to 2 m/s. The vibration velocity meter shall also be calibrated.

6.5 Current probe

The current probe shall be capable of measurement in a frequency range up to roughly five times the first (fundamental) resonance frequency of a piezoelectric fine ceramic resonator (material) and allow measurement of current in a range of approximately 1 mA to 1 A. The current probe shall also be calibrated.

6.6 Digital storage oscilloscope

The digital storage oscilloscope shall be capable of recording waveforms at a sampling frequency at least 10 times greater than the first (fundamental) resonance frequency of a piezoelectric fine ceramic and shall allow output of wave form data as numerical data. The oscilloscope should also allow recording of 1 s or more waveform data and have excellent y-axis resolution.

6.7 Test piece holder

The test piece holder shall have at its tip a pair of electrode pins measuring 1 mm or less in diameter and be capable of using these structures to sandwich and hold the upper and lower electrode surfaces of a piezoelectric fine ceramic resonator at a single point of contact on each surface.

NOTE 1 Providing the holder with a mechanism that has a Z-stage to move the upper pin vertically allows easy mounting of test pieces.

NOTE 2 If a thermocouple is installed inside the lower electrode pin, the temperature of a piezoelectric fine ceramic resonator can be measured easily.

6.8 Numerical analysis software (numerical analyser)

Numerical analysis software shall allow frequency analysis of waveform data and extraction of selected frequency components. The software shall also allow calculation of instantaneous frequency values and instantaneous amplitude values.

7 Specimens

7.1 Test piece form

A piezoelectric fine ceramic resonator is used as a test piece and has a form described as X (length, 43 ± 0,2 mm), Y (width, 7 ± 0,2 mm) and Z (thickness, 1 ± 0,05 mm), and an electrode surface described as length × width. Test pieces are also polarized in the orientation of their thickness.

To interface with laser light properly, laser-reflective surfaces (either of two surfaces comprising width × thickness) should be mirror-polished.

7.2 Measurement of test piece density

Test piece mass M is measured (weighing) in 1 mg units. Density ρ (kg/m^3) is then calculated from volume calculated on the basis of values described in 7.1, and rounded to four significant digits.

7.3 Measurement of characteristics values

Principal constants are measured in advance, for example test piece resonance frequency f_0, mechanical quality factor Q_m, elastic constant s_{11} and piezoelectric constant d_{31}.

NOTE EM-4501 is a useful reference on measurement methods for individual constants.

8 Measurement procedures

Measurement procedures are as follows.

a) Orient a test piece so that its thickness direction is vertical, and then support its central area by using the electrode pins of the test piece holder described in 6.7. Then direct the laser beam of the vibration velocity meter toward a lateral surface of the test piece.

b) Adjust function generator output and then apply a burst sine wave voltage e to excite the test piece at a vibration velocity at least 0,1 m/s higher than the maximum vibration velocity to be analysed.

The voltage amplitude and burst drive time (i.e. number of cycles applied) are used to adjust function generator output. At such times, frequency sweep driving can also be used. Keeping the drive time as short as possible minimizes the effect of heat generation due to vibration loss. Both the burst drive time and voltage amplitude can be selected as desired, but the burst drive time should be sustained for approximately 5 ms after the amplitude of vibration velocity stabilizes.

For example, when analysis uses a maximum value of 0,6 m/s as the vibration velocity, the test piece should be excited to a steady-state vibration velocity of 0,7 m/s or higher. On that basis, adjustment is first attempted by reducing the drive frequency f_d from the resonance frequency f_0 measured in 7.3, in decrements of approximately 0,1 kHz. If the test piece is still not excited to a high level, the voltage amplitude E of burst sine wave voltage can be raised to approximately +5 V for measurement, while again reducing drive frequency f_d.

c) Once the drive parameters are determined, record the vibration velocity waveforms and current waveforms. At this point, use the same drive parameters, but reduce the measurement range of the measuring instruments and the y-axis scale span of the digital storage oscilloscope, and then complete multiple recordings. Note that waveforms may also exceed the range. Also adjust sampling frequencies as per the test piece characteristics and make any necessary modification.

For example, assume that the vibration velocity measurement range (y-axis scale span) is set to a value such as 1,0 m/s/div., 0,5 m/s/div., 0,2 m/s/div. or 0,1 m/s/div. At such time, the measurement range for current may also be reset in the same way. If the Q_m value measured in 7.3 is 1 000 or greater, a value approximately 10 times the resonance frequency measured in 7.3 may be adopted as a guide for the sampling frequency. And if the Q_m value measured in 7.3 is 100 or lower, the sampling frequency may be raised, for example, to a value approximately 100 times greater than the resonance frequency.

d) After measurement is complete, measure such values as the principal constants again by following the procedure in 7.3, with a test piece held in the test piece holder.

9 Analytical procedures

This clause details analytical procedures for data. Figure 3 also presents an example of analytical procedures.

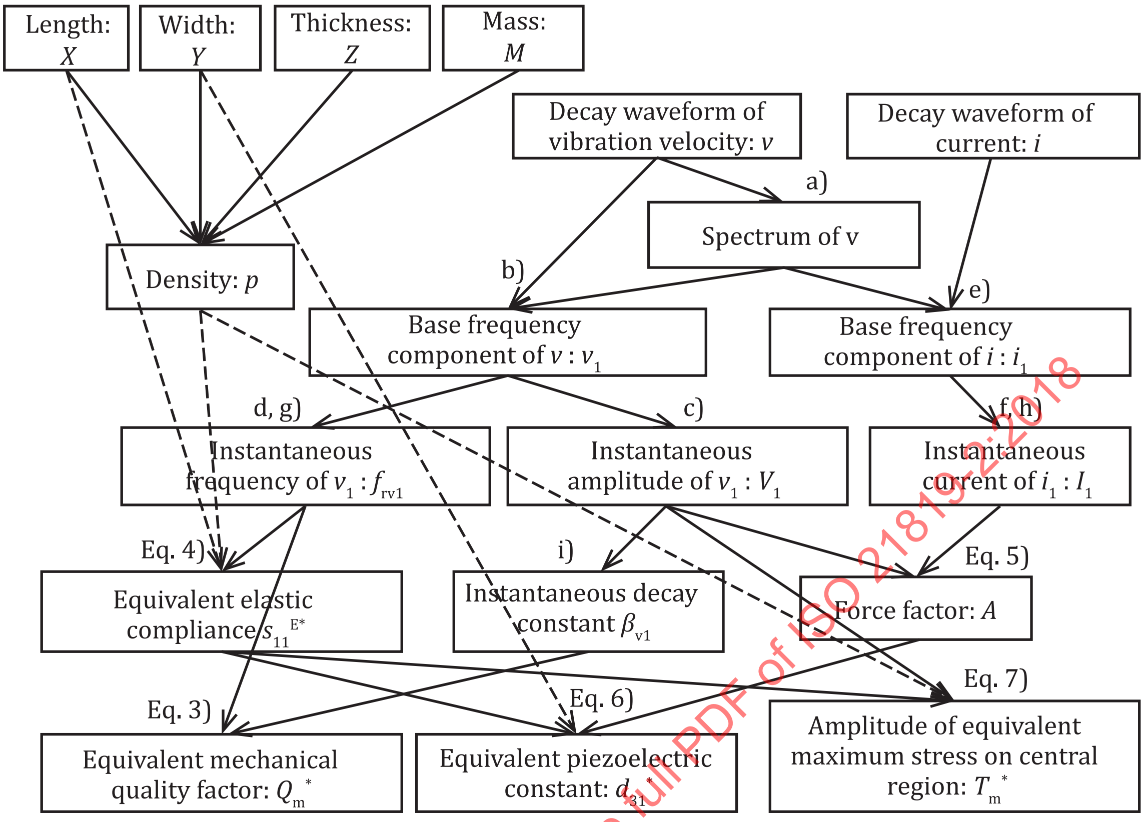


Figure 3 — Example of measurements by electrical transient response method and steps in calculation and analysis

a) Use numerical analysis software or similar means to calculate a spectrum for vibration velocity v versus time t data obtained by measurement.

b) Since data with a large amplitude range inevitably include various frequency components resulting from such factors as nonlinear phenomena, pass vibration velocity v versus time t data in the approximate range of the first (fundamental) frequency component through a band-pass filter to extract vibration velocity v_1 versus time t data for the first (fundamental) frequency component of vibration velocity alone.

For example, if the base resonance frequency is 40 kHz, a band-pass filter of approximately 30 to 50 kHz may be used to extract the first (fundamental) frequency component alone.

c) Use numerical analysis software or similar means to calculate the instantaneous amplitude value v_1 versus time t data for vibration velocity v_1 versus time t data pertaining to the first (fundamental) frequency component alone, as obtained in step b).

d) Use numerical analysis software or similar means to calculate the instantaneous frequency f_{rv1} versus time t data for vibration velocity v_1 versus time t data pertaining to the first (fundamental) frequency component alone, as obtained in step b).

e) For current, as in the case of the vibration velocity waveform, pass current i versus time t data in the approximate range of the base frequency component through a band-pass filter to extract current i_1 versus time t data for the first (fundamental) frequency component alone.

f) Use numerical analysis software or similar means to calculate the instantaneous amplitude I_1 versus time t data for current i_1 versus time t data pertaining to the first (fundamental) base frequency component alone, as obtained in step e).

For example, a calculation method may use a Hilbert transform procedure.

g) Let the instantaneous amplitude of the vibration velocity to be analysed be termed $V_{1(x)}$ and the point at the time termed $t_{(x)}$. Let the instantaneous amplitude of a vibration velocity 0,05 m/s greater than $V_{1(x)}$ be termed $V_{1(a)}$, and its corresponding time point termed $t_{(a)}$. Let the instantaneous amplitude of a vibration velocity 0,05 m/s less than $V_{1(x)}$ be termed $V_{1(b)}$, and its corresponding time point termed $t_{(b)}$. Use all data for the interval between $t_{(a)}$ and $t_{(b)}$ alone to draw a graph plotting instantaneous amplitude V_1 of vibration velocity on the x-axis and instantaneous frequency f_{rv1} of vibration velocity on the y-axis. Then calculate a quadratic approximation for this function by using the least-squares method, and use this approximation to determine instantaneous frequency $f_{rv1(x)}$ of vibration velocity at the time of $V_{1(x)}$.

NOTE For the calculation of the instantaneous frequency $f_{rv1(x)}$ of vibration velocity and the instantaneous frequency $f_{rv1(x)}$ of current in step i), the time interval need not be designated as the aforementioned range. In lieu of such designation, it is possible to use a wide data range to calculate a quadratic approximation by using the least-squares method.

h) As in step g), use all data for the interval between $t_{(a)}$ and $t_{(b)}$ alone to draw a graph plotting instantaneous amplitude V_1 of vibration velocity on the x-axis and instantaneous amplitude I_1 of current on the y-axis. Then calculate a first-order approximation for this function by using the least-squares method, and use this approximation to determine instantaneous amplitude $I_{1(x)}$ of current at the time of $V_{1(x)}$.

i) Draw a graph plotting t on the x-axis and log values $ln(V_1)$ of instantaneous amplitude V_1 of vibration velocity in the interval between $t_{(a)}$ and $t_{(b)}$ on the y-axis. Then calculate a first-order approximation (linear approximation) by using the least-squares method, and set the slope of the function as instantaneous decay constant $\beta_{v1(x)}$ for vibration velocity at the time of $V_{1(x)}$.

NOTE Both instantaneous frequency f_{ri1} and instantaneous decay constant β_{i1} of current can be calculated analogously, and compared with f_{rv1} and β_{v1} to serve as a reference.

10 Calculation of characteristic values

10.1 Calculation procedures for characteristic values

Calculate characteristic values as described as follows:

a) Use instantaneous amplitude $I_{1(x)}$ of current at the time of instantaneous amplitude $V_{1(x)}$ for a designated vibration velocity, instantaneous frequency $f_{rv1(x)}$ of vibration velocity, and instantaneous decay constant $\beta_{v1(x)}$ of vibration velocity in Formulae (3) to (7) to calculate required characteristics values Q_m*, $s_{11}{}^{E*}$, d_{31}* and T_m*. Repeat this procedure for the number of vibration velocity points used for calculation. Set the points of the vibration velocity used for calculation as 0,1 m/s interval data in the range from 0,1 m/s to 1,0 m/s, and be sure to include 0,6 m/s.

$$Q_m{}^* = \frac{\pi f_{rv1}}{\beta_{v1}} \tag{3}$$

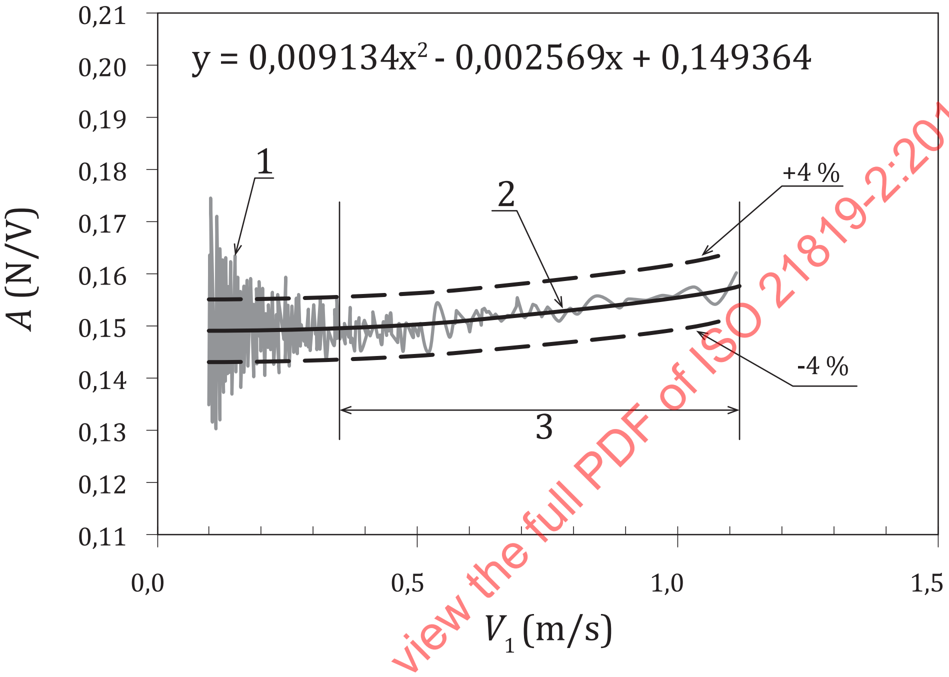
$$s_{11}{}^{E*} = \frac{1}{4\rho X^2 f_{rv1}} \tag{4}$$

$$A = \frac{I_1}{V_1} \tag{5}$$

$$d_{31}{}^* = \frac{s_{11}{}^{E*} I_1}{2YV_1} = \frac{s_{11}{}^{E*} A}{2Y} \tag{6}$$

$$T_m{}^* = \sqrt{\frac{\rho}{s_{11}{}^{E*}}} V_1 \tag{7}$$

b) Designate usable data ranges based on fluctuations in instantaneous frequency f_{rv1} of vibration velocity with respect to instantaneous amplitude V_1 of vibration velocity, and fluctuations in force factor A relative to instantaneous amplitude V_1 of vibration velocity. Specifically, plot instantaneous amplitude V_1 of vibration velocity on the x-axis and instantaneous frequency f_{rv1} of vibration velocity on the y-axis, and then use the data calculated through analysis to calculate a second-order approximation by using the least-squares method. Plot instantaneous amplitude V_1 of vibration velocity on the x-axis and force factor A on the y-axis, and then use the data calculated through analysis to calculate a second-order approximation by using the least-squares method.



Key

1 data

2 approximate expression

3 available area

Figure 4 — Example of designation of data range usable in analysis

The usable data shall be numerical data within the range that is both within ± 1 % of the second-order approximation in the first operation and within ± 4 % of the second-order approximation in the second operation. Figure 4 shows an example of designating usable data ranges.

10.2 How to obtain principal constants and round off characteristic values

Calculate the principal constants and characteristic values as follows.

a) Obtain integer values for the resonance frequency and instantaneous frequency of vibration velocity, and calculate the equivalent mechanical quality factor and instantaneous decay constant of vibration velocity to two decimals by rounding off at the third decimal place.

b) Calculate the elastic constant to three decimals by rounding off at the fourth decimal place.

c) Calculate the piezoelectric constant, equivalent elastic compliance and amplitude of equivalent maximum stress on the central region to two decimals by rounding off at the third decimal place.

d) Calculate the equivalent piezoelectric constant current to one decimal by rounding off at the second decimal place.

e) Calculate the instantaneous amplitude of current to four decimals by rounding off at the fifth decimal place.

11 Report of test results

The following items shall be reported for measurement:

a) number of this document, i.e. ISO 21819-2:2018;

b) measurement date, name of individual performing measurement;

c) test piece name, material, dimensions, mass and density as determined in 7.2 (see Annex A);

d) resonance frequency, mechanical quality factor, elastic constant, piezoelectric constant and other principal constants of the test piece as determined in 7.3 and Clause 8 d) (see Annex A);

e) manufacturer and model number of function generator, power amplifier, vibration velocity meter, current probe and digital storage oscilloscope used for measurement;

f) type of numerical analysis software (if a commercial item, manufacturer and model number) or numerical analyser (manufacturer and model number);

g) drive parameters (drive frequency, drive voltage, drive time) (see Annex A);

h) values analysed (V_1, I_1, β_{v1} and f_{rv1}) (see Annex A);

i) values of instantaneous frequency f_{ri} and decay constant β_{i1} of current, if determined;

j) characteristic values (Q_m*, s_{11}E*, d_{31}* and T_m*) derived from instantaneous amplitude V_1 of vibration velocity used in calculation (see Annex A);

k) other noteworthy information pertaining to measurements made.

