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Non-destructive testing — Acoustic emission testing — Verification of the receiving sensitivity spectra of piezoelectric acoustic emission sensors

Essais non destructifs — Contrôle par émission acoustique — Vérification des spectres de sensibilité de réception des capteurs d'émission acoustique piézoélectriques

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Foreword

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

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 9, *Acoustic emission testing*.

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

The proposed method of determining the receiving sensitivity spectra of a piezoelectric acoustic emission sensor is based on a setup where the face of the sensor under test is directly coupled via a thin layer of coupling agent to the active face of a piezoelectric transmitter. The transmitter, usually an ultrasonic probe, stimulates the sensor under test by a particle displacement pulse in normal direction to the sensor's face. The displacement pulse is measured by a vibrometer at a number of positions on the active area of the transmitter. This allows determining the transmitting sensitivity of the transmitter in absolute units of nm/V and the receiving sensitivity of the sensor under test in absolute units of V/nm.

The aim is to establish uniformity of acoustic emission testing, to form a basis for data correlation, and to provide a basis for the uniform interpretation of results obtained by different acoustic emission testing organizations at different times. For more information about the verification methods for piezoelectric sensors, see Annex C.

Non-destructive testing — Acoustic emission testing — Verification of the receiving sensitivity spectra of piezoelectric acoustic emission sensors

1 Scope

This document specifies a method for the determination of the receiving sensitivity spectra of a piezoelectric acoustic emission sensor, in absolute units of volts output per motion input, whereby the motion can be particle displacement (e.g. in nanometres) or particle velocity (e.g. in millimetres per second) over a frequency range used for acoustic emission testing, from 20 kHz to about 1,5 MHz, whereby the sensor is stimulated by a motion pulse in normal direction to the sensor's face from a directly coupled piezoelectric transmitter.

This document also specifies a method for the determination of the transmitting sensitivity spectrum of a piezoelectric transmitter in absolute units, for example, in nanometres output per volt input, by measuring both the particle displacement pulse over the transmitter's active face and the transmitter's input voltage spectrum, using a scanning laser vibrometer.

This document does not include the known cancellation effects on a sensor's response, when the angle of incidence differs from normal (90°) or when the length of the wave passing across the sensor's sensitive face is shorter than about 10 times the dimension of the sensor's sensitive face.

This document does not specify a method to measure the influence of different materials on a sensor's sensitivity, but this effect is addressed in Annex F.

NOTE The methods described in this document can be considered for use with other than piezoelectric sensors, which detect motion at a flat face and work in the same frequency range.

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 12716, *Non-destructive testing — Acoustic emission inspection — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12716 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
transmitter
TM
piezoelectric device that converts an electrical signal to particle motion or pressure

Note 1 to entry: A single-letter TM identifier (TM-id A to Z) may be appended to identify a certain unit of transmitter.

3.2
sensor under test
SUT
piezoelectric acoustic emission sensor whose *receiving sensitivity* (3.8, 3.9) spectra are verified

Note 1 to entry: A double-digit SUT identifier (SUT-id 00 to 99) may be appended to identify a type of SUT.

3.3
function generator
FG
electronic device for generating the stimulation pulse for the *transmitter* (3.1)

3.4
transient recorder
TRA
electronic device for waveform capture at two or more signal inputs with trigger input, pre-trigger capability and personal computer interface

3.5
scanning laser vibrometer
LVM
instrument for non-contacting measurement of particle motion in absolute units of nanometres at a number of positions on a surface in normal direction

3.6
face-to-face setup
arrangement where the active face of a *transmitter* (3.1) is directly coupled to the sensitive face of a *sensor under test* (3.2) for a reproducible stimulation by an electrical pulse

3.7
laser vibrometer setup
LVM setup
arrangement where a *scanning laser vibrometer* (3.5) is used to measure the particle displacement pulse at multiple positions at the free active face of a *transmitter* (3.1)

3.8
receiving displacement sensitivity
$\boldsymbol{R}_\mathbf{D}$
output voltage spectrum of a sensor in dB minus the particle displacement input spectrum in dB

Note 1 to entry: In this document, 0 dB of particle displacement sensitivity (R_D) refers to 1 V/nm,

Note 2 to entry: When the term "sensitivity" is clearly related to a *sensor under test* (3.2), the word "receiving" can be omitted.

3.9
receiving velocity sensitivity
$\boldsymbol{R}_\mathbf{V}$
output voltage spectrum of a sensor in dB minus the particle velocity input spectrum in dB

Note 1 to entry: In this document, 0 dB of particle velocity sensitivity (R_V) refers to 1 Vs/mm.

Note 2 to entry: When the term "sensitivity" is clearly related to a *sensor under test* (3.2), the word "receiving" can be omitted.

3.10
transmitting displacement sensitivity
$\boldsymbol{T}_\mathbf{D}$
output displacement spectrum of a *transmitter* (3.1) in dB minus its input voltage spectrum in dB

Note 1 to entry: In this document, 0 dB of particle displacement sensitivity (T_D) refers to 1 nm/V.

Note 2 to entry: When the term "sensitivity" is clearly related to a transmitter, the word "transmitting" can be omitted.

3.11
transmitting velocity sensitivity
$\boldsymbol{T_V}$
output velocity spectrum of a *transmitter* (3.1) in dB minus its input voltage spectrum in dB

Note 1 to entry: In this document, 0 dB of particle velocity sensitivity (T_V) refers to 1 mm/Vs.

Note 2 to entry: When the term "sensitivity" is clearly related to a transmitter, the word "transmitting" can be omitted.

3.12
Han2SQ
designation of a specific time window function applied to the input of the fast Fourier transform on the response of an acoustic emission sensor or of a laser vibrometer to a displacement pulse

Note 1 to entry: See D.2.3.

4 Symbols and abbreviated terms

D	displacement signal measured by LVM and converted to a spectrum with 0 dB referring to 1 pm peak; "*D*" may be appended by a TM-id (A to Z), a ring-id (1 to 5), and a window-id, see W7 below
FFT	fast Fourier transform, a method to convert a time-series signal into a frequency spectrum
MS/s	mega samples per second; "1 MS" means "1 million samples" NOTE: If a quantity of memory is given in "MS", "1 MS" usually means "2^{20}" (1 048 576) samples.
N_R	number of a ring of measurement positions in range 1 to 5, see 8.2
N_{RL}	largest ring number N_R of measurement positions (see Figure 6) covering the sensitive face of a type of SUT, for correct T_D selection, recorded in Table A.2
r_R	radius of ring number N_R in mm, see 8.2
R_{SS}	signal-to-stimulation ratio spectrum in dB, see Formula (4); the recommended naming of a specific R_{SS} data file begins with "S", followed by the SUT-id (00 to 99), the TM-id (A to Z) and a window-id, see W7 below
R_{VDD1}	drift detection sensitivity spectrum of drift detection sensor 1, for the verification of a transmitting sensitivity drift, see 8.7 c) 1)
R_{VDD2}	drift detection sensitivity spectrum of drift detection sensor 2, for the verification of a transmitting sensitivity drift, see 8.7 c) 1)
R_{VDR1}	drift reference sensitivity spectrum of drift detection sensor 1, determined with a transmitter's sensitivity determination according to 8.7 a)
R_{VDR2}	drift reference sensitivity spectrum of drift detection sensor 2, determined with a transmitter's sensitivity determination according to 8.7 a)
$R_{V\Delta 1}$	spectrum difference R_{VDD1} minus R_{VDR1} of drift detection sensor 1, see 8.7 c) 2)
$R_{V\Delta 2}$	spectrum difference R_{VDD2} minus R_{VDR2} of drift detection sensor 2, see 8.7 c) 2)

U_F transmitter voltage in face-to-face setup, stimulated by a function generator and measured by a transient recorder in the time domain, then transformed into the spectrum $F(U_F)$ in dB, with 0 dB referring to a sine wave of 1 mV peak

U_L transmitter voltage in LVM setup, stimulated by a function generator and measured by the LVM in the time domain, then transformed into the spectrum $F(U_L)$ in dB, with 0 dB referring to a sine wave of 1 mV peak

U_S sensor output voltage, also called "sensor response", measured by a transient recorder in the time domain, then converted into the spectrum $F(U_S)$ in dB, with 0 dB referring to a sine wave of 1 mV peak

$U_{SAV\%}$ average of 4 or 6 responses U_S from one SUT, stimulated by 4 or 6 transmitters, in per cent of its maximum peak-to-peak voltage, see Figure 7

$U_{S\Delta\%}$ deviation of the response U_S from $U_{SAV\%}$, with U_S in per cent of its maximum peak-to-peak voltage, see Figure 7

$F(D)$ FFT of the time signal D

$F(U_F)$ FFT of the time signal U_F

$F(U_L)$ FFT of the time signal U_L

$F(U_S)$ FFT of the time signal U_S

W5 identifier for a 4 µs main-pulse time window

W7 identifier for a 50 µs time window

W8 identifier for a 100 µs time window

W9 identifier for a 200 µs time window

5 Overview

5.1 Face-to-face setup — Block diagram

The block diagram of the face-to-face setup is shown in Figure 1 a). Numerical keys identify the blocks and alphabetical keys the interfaces. In this clause, the keys of Figure 1 are referenced in brackets.

The function generator (1) delivers the stimulation pulse U_F at the signal output (A) with a constant repetition rate.

The signal U_F (A) is connected to the input (D) of transmitter (2), and to the input channel B (J) of transient recorder (4). The electrical pulse stimulates a motion pulse at the transmitter's active face (E). This face is acoustically coupled via a thin layer of coupling agent (F) to the sensitive face (G) of the sensor under test (3). The sensor's signal output (H) delivers the sensor response U_S, which is connected to the input channel A (I) of transient recorder (4). The transient recorder signal capture is triggered at (K) by trigger output signal "Sync" (B) of function generator (1). The transient recorder (4) is under control of a personal computer (5) via interfaces (L) and (M).

The data captured of each trigger are read out via (L) and (M) by personal computer (5) and shown at the PC display in the time interval of the stimulation pulse, usually 200 milliseconds.

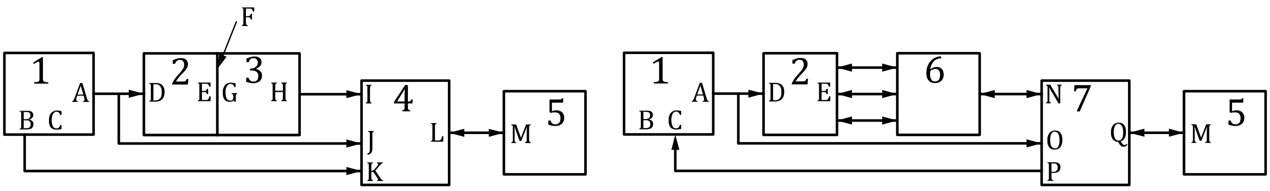
Stimulation pulse U_F (A) is shown in Figure D.1.

Examples of sensor responses U_S (H) of three types of sensors are shown in Figure D.6. to Figure D.8.

Not shown in Figure 1 is the fixture needed to align the centres of sensor and transmitter and to apply a force on the interface (E–F–G). The force required depends on properties of the coupling agent and on other forces that can apply, e.g. from the cable. A force of 10 N is recommended.

The operator may manipulate the fixture in order to see, if the coupling is stable or can be improved.

If satisfied with the reproducibility of the signal, the operator stops the capture repetition and stores the latest acquired signal into a properly named file.



a) Face-to-face setup

b) Laser vibrometer setup

Key

1 function generator (FG) with signal output key A, sync output key B and trigger input key C

2 transmitter with pulse input key D and displacement output at its active face key E

3 sensor under test (SUT) with displacement sensitive input key G and response voltage output key H

4 transient recorder (TRA) with channel A input key I, channel B input key J, trigger input key K, and PC interface key L

5 personal computer (PC) with interface key M

6 laser scan positioning unit for 21 positions at the active transmitter face key E

7 scanning laser vibrometer (LVM) with optical input key N, reference voltage input key O, and trigger output key P

A FG output signal U_F in face-to-face setup, U_L in LVM setup, the stimulation pulse

B FG trigger output “Sync” to key K, open in LVM setup

C FG trigger input, from key P, open in face-to-face setup

D transmitter input signal U_F from key A

E transmitter output motion at its active face to key G in face-to-face setup, to key 6 in LVM setup

F coupling agent at the TM-to-SUT interface, also called "couplant", see ISO 12716:2001, 2.15

G SUT input motion at its sensitive face, from key E in face-to-face setup

H SUT output signal U_S to key I in face-to-face setup

I TRA input channel A, measures U_S from key H

J TRA input channel B, measures U_F from key A

K TRA trigger input from key B

L TRA to PC interface, TRA-side

M PC in-/output from/to key L in face-to-face setup or key Q in LVM setup

N LVM laser beam sequentially positioned by key 6 to one of 22 positions at the TM face key E

O LVM reference voltage input signal U_L, from key A

P LVM trigger output to FG, key C

Q LVM to PC interface, LVM side

Figure 1 — Block diagrams of the face-to-face setup and the laser vibrometer setup

The face-to-face setup as described in Figure 1 can be used for sensors with and without integral pre-amplifier, see 6.6.3.

5.2 Laser vibrometer setup — Block diagram

The laser vibrometer technique should be used for determining the transmitting sensitivity of a transmitter to be used in the face-to-face setup.

This shall be performed:

a) after a transmitter's purchase;

b) whenever the transmitter has been exposed to extraordinary conditions, e.g. to a mechanical or thermal shock; and

c) once every year.

The block diagram of the laser vibrometer setup is shown in Figure 1 b). It is similar to 1 a). Instead of a sensor under test (3), a laser vibrometer (7) measures the motion pulse at the transmitter's active face whereby the laser beam is sequentially positioned by (6) to one of 22 measurement positions, whereby position 22 is the same as position 1, see Figure 6.

The stimulation pulse U_L is generated by function generator (1) at signal output (A) in response to trigger input (C), generated by laser vibrometer (7), output (P). The transmitter input U_L is usually the same as U_F in the face-to-face setup.

If a post-amplifier is used to drive the transmitter, for a better signal-to-noise ratio of the displacement result, the voltage (O) shall be measured at the post-amplifier output.

The laser vibrometer is under control of a personal computer (5) which reads out the acquired data via (Q) and (M).

For the improvement of the signal-to-noise ratio, the laser vibrometer measurements shall be repeated and averaged ten thousand times for each measurement position, followed by a de-noising Savitzky-Golay filter 3rd order, 41 samples.

Then a displacement of about 2 picometer can be separated from noise. This is about 0,2 % of the displacement maximum of about 1 nm peak-to-peak with the function generator amplitude set to the maximum (10 V peak-to-peak).

6 General requirements related to hardware

6.1 General

This clause defines general requirements related to hardware items for the face-to-face setup for achieving optimal results for the determination of receiving sensitivity spectra of a sensor under test (SUT). For the requirements related to the hardware of the laser vibrometer setup, see 8.2. For examples of the equipment, see Annex B.

6.2 Requirements related to the function generator (FG)

The requirements in the following list are tuned to specified characteristics of a commercially available function generator. For an example, see B.1.

A function generator PC board of comparable functionality and specifications, e.g. controllable by software only, may be chosen alternatively.

a) The function generator shall be controllable by software via a standard interface, e.g. USB or LAN.

b) The output impedance shall be 50 Ω, the maximum amplitude setting 10 V peak-to-peak or more. The amplitude setting shall apply at 50 Ω termination. If the output is open, the output voltage shall be twice the voltage setting.

c) The function generator shall support the generation of a sine wave in a single-cycle burst mode with a starting phase of 90°, so the output moves once per trigger from +10 V to -10 V and back to +10 V.

d) A burst shall be generated in response to an internal trigger in a user defined time interval (in face-to-face setup) and to an external trigger (in laser vibrometer setup) and to a software command.

e) The function generator shall provide a trigger output ("Sync"), when it is internally triggered.

f) The harmonic distortion at 1 MHz 10 V peak-to-peak shall be -45 dB maximum.

g) The inaccuracy of the output signal shall be ±1 % setting ±1 mV maximum at 1 kHz.

h) The amplitude flatness relative to 1 kHz shall be 0,15 dB maximum at 1 MHz.

i) The output sampling rate shall be at least 40 MS/s.

j) For the avoidance of ground loop noise in the measurement chain, the function generator's internal ground, usually connected to the shielding of the output and sync connectors, shall remain isolated from protective earth for at least ±5 V. A terminal for the internal ground shall be available for an optional external protective ground connection.

k) Periodic calibration of the function generator is recommended but not a requirement, since the signal output is measured by the transient recorder, which shall be periodically calibrated.

6.3 Requirements related to the transmitter

The following requirements a) and b) related to the transmitter describe an ideal example.

This document recommends the use of a commercially available ultrasonic probe, see B.2.

The accuracy and reproducibility of the results of the face-to-face setup is limited by variations of properties of the used transmitter, especially during the reverberation phase that follows the active pulse.

An important objective of this document is to initiate the development of a transmitter type which comes close to the ideal.

a) The transmitter shall employ a piezo element with almost perfect rear-side damping for the reflection-free absorption of particle motion.

b) The diameter of the active face of the piezo element shall be sufficient to stimulate the sensitive face of up to 25 mm diameter of a sensor under test (SUT) by a particle motion, usually a displacement pulse, evenly distributed from centre to edge.

c) Using a unipolar cosine-shaped pulse of 20 V peak shall generate a displacement pulse of about 1 nm, see Figure E.2 a).

d) The capacitance of the piezo element, measured at 1 kHz, shall not exceed 2 nF.

e) For each transmitter unit to be used, the transmitting sensitivity shall be determined according to Clause 8, or another procedure of equivalent accuracy, so that the displacement spectra at the input of the SUT in the face-to-face setup can be reconstructed from the spectrum of the stimulation pulse and the spectra of the transmitting sensitivities.

f) If the motion across the active area of the transmitter is not uniformly distributed and varies with the centre distance, different transmitting sensitivities for different diameters of the sensitive areas of different types of SUTs shall be determined.

g) Details about each transmitter unit shall be kept in a transmitter list. See A.1 for a template of such lists.

h) Some manufacturers of piezoelectric transmitters recommend not to apply a permanent DC voltage at the transmitter. In such a case, it is recommended to insert a DC blocker (a shielded, non-polarized capacitor of 10 µF/50 V) between the cable and the terminal of the transmitter, see key D in Figure 1 a) and b).

6.4 Requirements related to the coupling agent between transmitter and sensor under test

The coupling agent shall:

a) provide an optimal coupling quality within 15 s after application (some sorts of grease exhibit delays that can last hours);

b) provide a coupling quality that remains constant over the intended duration of a verification job, usually a few minutes;

c) be highly fluid (low viscosity) to achieve requirement a);

d) not be toxic for the skin, to avoid the need for protective gloves;

e) not be toxic for the eyes or other organs;

f) neither cause a damage at the sensor, nor the transmitter nor the holding fixture;

g) be easily removable from any surface.

6.5 Requirements related to the sensor-to-transmitter fixing tool

6.5.1 General

Figure 2 shows an example solution to provide alignment of the centres of sensor and transmitter.

Figure 2 a) shows the parts needed for a sensor of about 20 mm diameter (key 5); and Figure 2 b) shows a complete fixture whereby a sensor of about 6 mm diameter is mounted on top of the transmitter, aligned by a diameter-matching sensor fixing ring and pressed down by a leaf spring.

The distance ring (key 3 in Figure 2 a) is to separate the sensor fixing ring (key 4) from the transmitter in order to avoid disturbances in the sensor response spectra.

6.5.2 Requirements

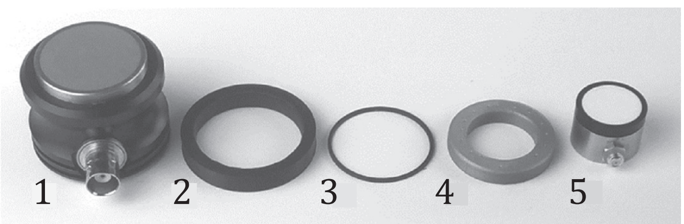
The sensor-to-transmitter fixing tool shall:

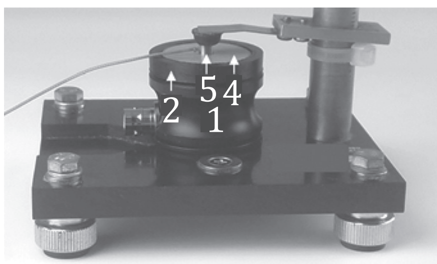
a) fix the centre of the sensor aligned to the centre of the transmitter and put a force of at least 10 N on the coupling agent between sensor and transmitter;

b) allow for a small movement between sensor and transmitter to let the operator see at the signal on the PC display that coupling quality is good and stable;

c) provide a defined angular relation between sensor and transmitter, e.g. zero degrees between both sideward mounted connectors;

d) not influence or hinder the motion transfer from transmitter to sensor, e.g. by design or material properties of the fixing tools.





a) Parts of a sensor-to-transmitter fixture **b) Fixture holding a small-diameter sensor**

Key

1 transmitter with active face looking upward
2 ring to be put over the transmitter face for centring the other rings
3 distance ring ensuring 1 mm distance between transmitter and sensor fixing ring
4 sensor fixing ring (such a ring is needed for each diameter of sensors to be verified)
5 sensor under test

Figure 2 — Example of a sensor-to-transmitter fixing tool

The recommended dimensions of keys 2 to 4 in Figure 2 are as follows.

e) The inner diameter of key 2 should equal the diameter of the cylindric part visible around the active face of key 1 plus (0,05 mm to 0,15 mm); and this should equal the outer diameters of key 3 and key 4.

f) The outer diameter of key 2 should equal the inner diameter plus (9 mm to about 20 mm); and the thickness should equal twice the height of the cylindric part of key 1 minus 0,1 mm, in order to allow for a direct contact with a SUT of same geometry as key 1.

g) The inner diameter of key 3 should equal its outer diameter minus (2 mm to 4 mm).

h) The inner diameter of key 4 should equal the diameter of the SUT plus (0,05 mm to 1,5 mm).

i) The thickness of key 4 should equal 5 mm minus (0 mm to 0,5 mm).

j) The mentioned tolerances of the outer diameter of key 2 and the inner diameter of key 4 allow for a small movement of the SUT on the TM.

k) Key 3 may be realized by an O-ring of 1 mm diameter of the cord and an inner diameter of key 1 diameter minus 2 mm. Its purpose is to hinder the coupling of the TM's motion to key 4, which would disturb the sensitivity result for a SUT of small diameter at high frequencies.

All parts of the prototype rings shown in Figure 2 a) are produced by a 3D-printer.

6.6 Requirements related to the sensor under test (SUT)

6.6.1 General

The most commonly used acoustic emission sensors are of single-ended construction and employ a coaxial cable connector. Sensors of differential construction are often equipped with an integral cable ending in a two-pole plus shielding connector. An adapter for the connection of a differential sensor to a single-ended input of the transient recorder can then be required.

6.6.2 Pyroelectric effect

Piezoelectric sensors are subject to the pyroelectric effect, meaning that a change of temperature acts like a change of pressure and causes electric charge. If a sensor does not employ a discharge resistor in range 10 MΩ to 100 MΩ, a change of the temperature can cause a high voltage stored in the capacitance of the piezo element. When the sensor is then connected to the transient recorder, it can be damaged by the discharge current.

If the presence of such discharge resistor is unknown, the resistance of the sensor can be measured. If no discharge resistor is present, it is good practice to discharge stored energy by shortly connecting a standard 50 Ω terminator to the sensor, before connecting the sensor to an instrument. Sensors with

