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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

Reference number
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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
$\boldsymbol{R_D}$
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
$\boldsymbol{R_V}$
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
$\boldsymbol{T_D}$
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
$\boldsymbol{T}_{\mathbf{V}}$
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.

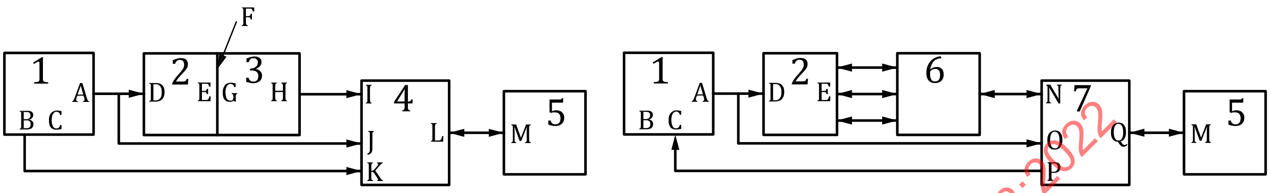
Stimulation pulse U_F (A) is shown in Figure D.1.

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

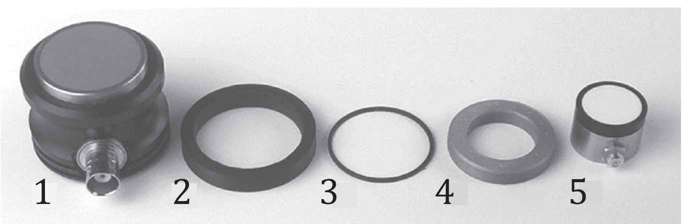
The sensor-to-transmitter fixing tool shall:

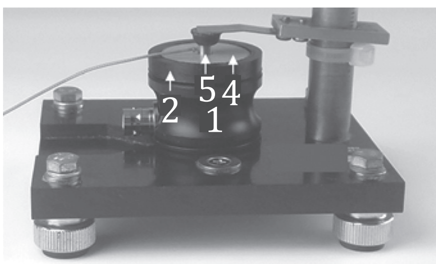
a) fix the centre of the sensor aligned to the centre of the transmitter and put a force of at least 10 N on the coupling agent between sensor and transmitter;

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 integrated pre-amplifiers are usually internally protected against a damage from the pyroelectric effect.

6.6.3 Integrated pre-amplifier

For sensors with integrated pre-amplifier, the normal power supply for that sensor should be used.

If the power voltage is fed-in via the signal output, a BNC-T-piece may be used for the connection of the cable to the transient recorder.

The amplitude of the stimulation pulse shall be set for 50 % to 90 % of the full-scale pre-amplifier output.

The amplitude of the stimulation pulse is measured and considered in the formula for sensitivity calculation, see Formula (4).

Only for the verification of sensors with integral pre-amplifier, a verified AE system (stand alone or PC board) may be used instead of a transient recorder (see 6.9).

6.6.4 Influence of the pre-amplifier input impedance

If the sensor is normally used with an external pre-amplifier of less than 1 MΩ input impedance, the sensitivity of the combination of sensor and pre-amplifier is lower than determined by the normal face-to-face setup due to the additional load. In the case of an input impedance of 10 KΩ, the reduction in sensitivity has been determined to 0,5 dB at 100 kHz; 1,7 dB at 50 kHz; 3,8 dB at 25 kHz; 6 dB at 20 kHz.

The sensitivity spectrum of the combination of sensor and pre-amplifier can also be influenced by the spectrum of the pre-amplifier's gain.

6.6.5 Requirements for a list of sensors under test

Each sensor type to be verified shall be registered in a SUT list with all information required for the use in the face-to-face setup and for selecting the suited transmitting sensitivity according to the size of the sensitive face. For a template of a SUT list, see A.2.

6.7 Requirements related to the signal cable from sensor to transient recorder

6.7.1 General

The sensor cable is usually a coaxial cable with coaxial connectors. The sensor cable can be removable or non-removable at the sensor side. Differential sensors usually use an integral shielded two-pole cable with a two-pole plus shielding connector. Since the capacitance of the sensor cable decreases the voltage generated by the piezo electric effect, the length of the sensor cable influences the sensor’s sensitivity.

6.7.2 Requirement

If the sensor cable is removable from the sensor, the measurements shall be made using a cable length between 20 cm and 30 cm in order to obtain comparable sensitivity spectra.

A cable longer than 30 cm may be used, if the influence on the sensitivity result has proven to be less than 1 dB.

6.8 Requirements related to the signal cable from the function generator to the transmitter and to the transient recorder

The total length of these two coaxial cables is not problematic, because the voltage source is of low impedance, compared to a piezoelectric element, and the transmitter voltage (U_F) is measured and considered for sensitivity determination.

However, the voltage pulse from function generator drives about 200 mA peak-to-peak. The voltage then drops off about 18 mV peak-to-peak at the cable shield at the transmitter side against the function generator side in the case of a 75 cm long cable.

Depending on the shield crosstalk of the SUT, a crosstalk of that pulse can reach the sensor output and disturb the results. See 7.4.6 for a crosstalk test.

6.9 Requirements related to the transient recorder for measuring U_S and U_F

6.9.1 General

For minimizing uncertainties concerning the coupling quality, the use of a transient recorder with PC display and sufficient storage capabilities is recommended. Such combination presents the captured waveforms immediately at the PC screen in a convenient time interval. The operator may manipulate the sensor to transmitter coupling and select the best coupling situation for permanent data storage.

The requirements given in 6.9.2 to 6.9.6 match the technical data provided for a commercially available model of an oscilloscope front-end, see B.3.

Instead of a transient recorder, a verified AE system (stand alone or PC board) and a verified wide-band pre-amplifier may be used.

But be aware that at the time of the stimulation pulse, the pre-amplifier draws a short high-supply current pulse which causes a disturbing voltage drop on the signal output.

Therefore, this document does not recommend the use of an acoustic emission pre-amplifier for the sensitivity verification of passive sensors. See 6.6.3.

6.9.2 Input impedance

As mentioned in 6.7 for the sensor cable, the capacity in parallel to the sensor's piezo element and also the resistance can influence the obtained sensitivity. Therefore, the input impedance shall be specified close to 1 MΩ parallel to 13 pF.

6.9.3 Range, resolution, accuracy, sampling rate and buffer length

The following requirements shall be met.

a) The input voltage range shall be specified from ±10 mV to ±20 V full scale.

b) The protection against overvoltage shall not load the input for signals below ±50 V.

c) A measurement mode with 15-bit vertical resolution and two active input channels shall be selected.

d) The DC inaccuracy shall be specified close to ±1 % of full scale, for the measurement range of 50 mV or more, at 20 °C to 30 °C environmental temperature.

   AC mode should be selected for both channels.

e) A sampling rate of 40 MS/s and a data buffer of 8 KS is sufficient to obtain 40 samples over 1 µs width of the stimulation pulse and about 200 µs signal data.

f) With the recommended model, the sampling rate depends on the selected combination of channel numbers, digitizer resolution, and buffer length.

   For the recommended sampling rate of 125 Ms/s (8 ns interval), 2 active channels, 15-bit digitizer resolution, a buffer length of 500 µs and 64 K samples should be selected.

g) For very low-voltage measurements, the vertical axis scaling shall be supported by an additional factor (e.g. 10 or 20) for a zoom into the selected full-scale range, e.g. ±10 mV, see 7.4.6.

6.9.4 Bandwidth

For minimum noise, a low-pass filter with a corner frequency between 4 MHz and 8 MHz should be selected.

6.9.5 Trigger settings

The trigger shall be set to repeat mode, external input (from the "Sync" output of the function generator), 100 mV trigger level, rising edge, 1 % pre-trigger. The pre-trigger data are used for DC-offset determination and compensation.

6.9.6 Verification — Calibration

The transient recorder shall be periodically calibrated, or its accuracy shall be verified according to the instructions of the manufacturer.

7 Determination of the receiving sensitivity spectra

7.1 General

The stimulation signal U_F from the function generator (FG), fed into the transmitter, generates a particle displacement pulse D of sufficient amplitude and frequency content.

This document recommends a single-cycle sine-wave pulse of 1 MHz, starting at 90°. This results in a negative going cosine pulse. For details about the stimulation signal, see Annex D.

The sensor under test (SUT), when directly coupled to the transmitter, using a coupling agent in-between, converts the particle displacement pulse to the output signal U_S. Both signals, U_F and U_S, are digitized by the transient recorder and stored to hard disk. The digitized data are then DC-offset compensated. For details see D.1.2.

Since the sampling interval of the used transient recorder is 8 ns, the digitized data are down-sampled to a 25 ns interval and by FFT transformed to the frequency domain. For details, see D.1.3 and D.2. For examples of responses of a wide-band sensor, a 150 kHz narrow-band sensor and a low-frequency sensor, see D.3.

7.2 Formulae for the determination of receiving sensitivity spectra R_D and R_V

The term receiving displacement sensitivity (R_D) of a sensor defines the difference between the output voltage spectrum and the input displacement spectrum, both converted to dB.

In this document, 0 dB of receiving displacement sensitivity (R_D) refers to 1 V/nm, which equals 1 mV/pm.

Formula (1) follows from the above: the sensitivity spectrum R_D in dB, with 0 dB referring to 1 mV/pm, equals the spectrum of the sensor output U_S in dB, with 0 dB referring to 1 mV, subtracted by the spectrum of the displacement input D in dB, with 0 dB referring to 1 pm.

$$R_D = F(U_S) - F(D) \qquad (1)$$

The displacement spectrum D can be determined by Formula (2). The displacement spectrum $F(D)$ in dB, with 0 dB referring to 1 pm, equals the spectrum of the stimulation pulse $F(U_F)$ in dB, with 0 dB referring to 1 mV, added by the transmitting displacement sensitivity T_D in dB, with 0 dB referring to 1 pm/mV. The transmitting displacement sensitivity of the used transmitter can be determined as described in Clause 8.

$$F(D) = F(U_F) + T_D \qquad (2)$$

$$R_D = F(U_S) - F(U_F) - T_D \quad (3)$$

$$R_{SS} = F(U_S) - F(U_F) \quad (4)$$

$$R_D = R_{SS} - T_D \quad (5)$$

Replacing $F(D)$ in Formula (1) by the right side of Formula (2) leads to Formula (3).

The spectral difference $F(U_S) - F(U_F)$ in Formula (3) is called "signal-to-stimulation ratio" (R_{SS}), see Formula (4), which leads to Formula (5).

The signal-to-stimulation ratio R_{SS} is obtained from face-to-face setup and the transmitting displacement sensitivity T_D from laser vibrometer setup, see Formula (9) in 8.1.

For determination of the receiving velocity sensitivity R_V, Formula (5) is converted to Formula (6) where R_D and T_D are replaced by R_V and T_V, respectively. The transmitting velocity sensitivity T_V is the differentiation of T_D, which is obtained by Formula (7), see 7.5.5 in Reference [5].

$$R_V = R_{SS} - T_V \quad (6)$$

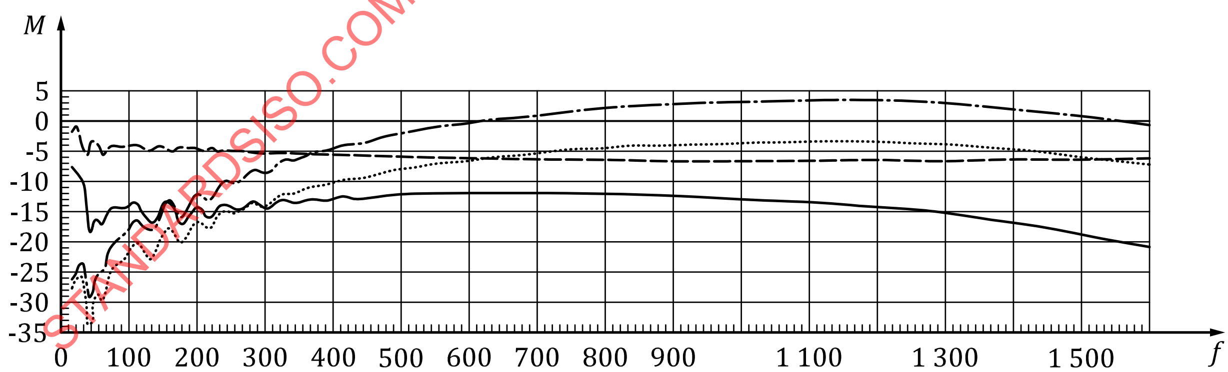
$$T_V = T_D + (20 \times \lg(2\pi f) - 120) \quad (7)$$

$$R_V = R_D - (20 \times \lg(2\pi f) - 120) \quad (8)$$

where f is the frequency in kHz.

Applying Formula (7) to Formula (6) leads to Formula (8), which delivers the receiving velocity sensitivity R_V in dB, with 0 dB referring to 1 Vs/mm. The subtraction of 120 dB in Formula (7) causes the change of "nm" to "mm" in the unit of T_V, with 0 dB referring to 1 mm/sV.

7.3 Relevant spectra for sensor sensitivity verification



Key

M	magnitude of FFT, in dB
f	frequency, in kHz
—·—	receiving displacement sensitivity spectrum R_D in dB, with 0 dB referring to 1 V/nm
———	receiving velocity sensitivity spectrum R_V in dB, with 0 dB referring to 1 Vs/mm
....	signal-to-stimulation ratio R_{SS} in dB, with 0 dB referring to 1, +20 dB curve shift up
– – – –	transmitting displacement sensitivity spectrum T_D in dB, with 0 dB referring to 1 nm/V, +20 dB curve shift up

Figure 3 — Relevant spectra for the sensor sensitivity determination of a wide-band sensor

Figure 3 shows the relevant spectra for sensor sensitivity verification from 20 kHz to 1 600 kHz for the following conditions:

— transmitter used: TMA;

— sensor under test: SUT01;

— transmitting sensitivity T_D derived from positions 1 to 13 (rings 0 to 3, see Figure 6);

— LVM data filter applied: Savitzky-Golay filter of 3rd order, 41 samples, over the reverberation phase;

— FFT window for R_{SS} and T_D: W7 (Han2SQ, 50 µs length, see D.2.3).

In Figure 3:

— the dot and dash line shows the receiving displacement sensitivity R_D, defined by Formula (5);

— the solid line shows the receiving velocity sensitivity R_V, defined by Formula (8);

— the dashed line shows the transmitting sensitivity T_D, defined by Formula (9) in 8.1, shifted up by 20 dB;

— the dotted line shows the signal-to-stimulation ratio R_{SS}, defined by Formula (4), also shifted up by 20 dB into the vertical scale optimized for R_D and R_V;

— the dot and dash line R_D corresponds to the dotted line minus the dashed line.

The apparent receiving sensitivity is more or less influenced by the difference of the acoustic impedances of the sensor material and of the material the sensor is mounted to. More information about this can be found in Annex F.

7.4 Procedure for sensor sensitivity verification

7.4.1 Preparation

The following steps shall be performed.

a) For the requirements related to the transmitter, see 6.3.

   1) Before a first sensitivity verification can be done, at least one verified transmitter shall be made available.

   2) The transmitting sensitivity of that transmitter shall be determined according to Clause 8 for five diameters of the active transmitter area. The reason for this is the non-uniform motion distribution across the transmitter's active area.

   3) The designations of the transmitting sensitivities to be used are listed in Table 1 and explained in 8.2.

b) The third character in the last column of Table 1 addresses the transmitter (TMA).

   For the procedure to determine the transmitting sensitivity, see 8.3.

c) Decide on a transmitter-to-sensor fixing tool (see 6.5).

   The main purpose of the fixing tool is to achieve a precise alignment of the centre points of the faces of sensor and transmitter and the application of a constant pressure on the coupling agent between sensor and transmitter.

   A horizontal setup of the TM to SUT interface avoids that low-viscosity couplant, e.g. light oil, runs out.

d) Decide on a coupling agent.

Light oil or even hand milk have proven to provide stable coupling conditions within a few seconds.

Higher-viscosity coupling agents, like silicon grease, can need hours to stabilise.

e) Get all other items ready which are listed in Figure 1, keys 1, 3, 4 and 5 according to the corresponding requirements in Clause 6.

f) If the SUT employs a pre-amplifier, refer to 6.6.3.

g) It is recommended to manage a list of sensor types to be (and have been) verified, including the SUT type identifier (00 to 99), the serial number, the manufacturer and the diameter of the sensitive face of each sensor type. See the example in A.2.

h) It is recommended to manage a list of transmitter units, which includes the transmitter identifier (A to Z). the transmitter type and serial no, and the temperature at the time of displacement measurements for the laser vibrometer setup, usually about 24 °C to 26 °C. See the example in A.1.

i) Since the transmitting sensitivity is slightly temperature dependent, an optimum reproducibility is obtained, when the pair of transmitter and SUT is settled to the average of the temperatures before and after the displacement measurements with the laser vibrometer setup, as recorded in the transmitter list.

j) Some simple software scripts shall be prepared for the conversion of U_F (stimulation pulse) and U_S (sensor response) into the spectra $F(U_F)$, $F(U_S)$ and R_{SS} (signal-to-stimulation ratio) according to Formula (5).

k) For most SUT types a window length of 50 µs applies; for low-frequency sensors of 100 µs.

For details about the signal processing in the time domain, see D.1. For relevant effects of the FFT, see D.2. For examples of result spectra of different types of SUT, see D.3.

7.4.2 Cable connections for the face-to-face setup

Connect cables as indicated in Figure 1.

a) Connect the function generator signal output (key A) via a T-piece at the function generator output to the transmitter (key D), and to the transient recorder input channel B (key J), by using 2 coaxial cables.

b) If the SUT provides a cable connector instead of an integral cable, use a 20 cm to 30 cm long coaxial cable with proper connectors from the sensor output (key H) to the transient recorder input channel A (key I).

Otherwise connect the integral sensor cable to the transient recorder.

NOTE Using a 100 cm coaxial cable, instead of 30 cm, causes about 2 dB lower sensor response at 100 kHz, and about 3 dB at 1,5 MHz due to the higher cable capacitance.

c) Use a coaxial cable to connect the function generator output "Sync" (key B) to the transient recorder's trigger input (key K).

d) Connect the transient recorder (key L) to the PC (key M).

e) Connect the power cables of the function generator, PC, and transient recorder to the power outlet and switch on all devices.

7.4.3 Settings of the function generator in the face-to-face setup

The following applies for a function generator model given in B.1.

a) Waveform: sine wave

b) Frequency: 1 MHz

c) Amplitude: 10 V peak-to-peak

d) Sweep: off

e) Burst: on

f) Start phase: 90°

g) Trigger: internal, 200 ms interval (for 200 ms PC-display update)

h) Output: on

7.4.4 Setting of the transient recorder

The following applies for a transient recorder type given in B.3.

a) Operation mode: time-based, persistence off, spectrum off

b) Buffer time: 500 µs, 50 µs per division

c) Buffer size (for 125 MS/s) 64 kS

d) Vertical resolution: 15 bits

e) Horizontal zoom: ×10

f) Trigger: repeat

g) Trigger input: external rising

h) Trigger level: 100 mV

i) Pre-trigger: 1 % (=5 µs of 500 µs buffer length)

j) Time delay: off

k) Channel A: on

l) Vertical scaling: auto

m) Input mode: AC

n) Probe: ×1

o) Low-pass filter: 8 MHz

p) Bandwidth limit: 20 MHz

q) Axis scaling: ×1

r) Axis offset: 0,0

s) Channel B: as channel A, from l) to r)

t) Channel C: off

u) Channel D: off

Measurement display 1:

v) Channel: A

w) Type of measurement: peak-to-peak

x) Section of graph: whole trace

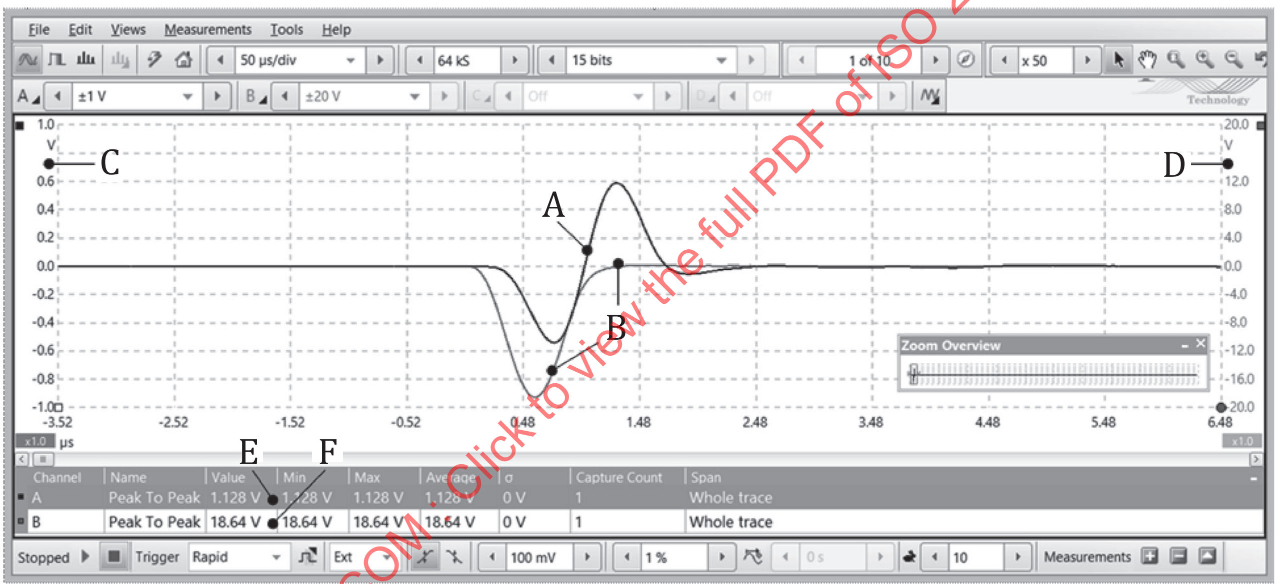
Measurement display 2:

y) Channel: B

z) Type of measurement: peak-to-peak

aa) Section of graph: whole trace

7.4.5 Trial measurement



Key

A input A of transient recorder, SUT output U_S

B input B of transient recorder, stimulation pulse U_F at transmitter input

C left-hand axis scale for the curve of channel A

D right-hand axis scale for the curve of key B

E display of numeric peak-to-peak value of channel A (U_S)

F display of numeric peak-to-peak value of channel B (U_F)

Figure 4 — Screen shot of a PC display of a trial measurement

a) It is recommended to finalize the preparation phase by a trial measurement with a transmitter coupled face-to-face to a wide-band sensor with coupling agent in between.

b) All connections shall be made according to 7.4.2.

c) All settings of the function generator and the transient recorder shall be made according to 7.4.3 and 7.4.4.

d) The measured curves for the stimulation voltage from function generator (U_F) shall look like key B in Figure 4.

e) When using a wide-band SUT the signal of the sensor output (U_S) shall look like key A in Figure 4.

The display of Figure 4 should be updated according to the setting of the burst time interval of the function generator (about 200 ms).

In Figure 4 the horizontal scale shows time in microseconds. 0 µs corresponds to the time of trigger. The time axis in Figure 4 is zoomed by a factor of 50 for a better resolution.

7.4.6 Initial crosstalk test

In order to assure that cabling is perfect and no disturbing crosstalk from transmitter shielding to sensor output disturbs the results, the following simple crosstalk test shall be performed once.

a) While the function generator delivers periodically stimulation pulses to the transmitter, as seen as line B in Figure 4, remove the SUT from transmitter. Line A is at 0 V.

b) Set the transient recorder input channel A to range ±10 mV. Set "Channel A axis scaling" to a factor of 10, what results in a 0,2 mV/division axis scaling.

c) Press the shielding of the connectors of TM and SUT together for a good electrical contact, avoiding any acoustic coupling. A small noise-contaminated negative-going pulse of less than 0,2 mV peak (instead of line A in Figure 4) is normal. A value larger than 1,2 mV peak indicates a crosstalk problem. Then minimize the cable length from function generator to transmitter or use a second coaxial cable in parallel to reduce the voltage drop via the cable shielding.

d) Report the pulse voltage maximum measured by channel A as crosstalk. See an example in Table 2, No. 11.

7.4.7 Capturing data of the sensor under test — Stimulation pulse U_F, sensor response U_S

It is assumed that steps 7.4.1 to 7.4.6 have been successfully performed. Then proceed as follows.

a) Mount the SUT to the TM with fresh coupling agent in-between, both fastened by the fixing tool. The angle between the sideward connectors of TM and SUT shall always be the same, so it is the easiest way; both connectors show to the same direction.

b) Start triggering pulse signals by the function generator as described for trial measurements in 7.4.5.

c) Let the pair of transmitter and sensor under test settle to the temperature which has been recorded in the transmitter list.

   Measure the temperature at the transmitter and record it in the report template.

d) If the output of an integral or external pre-amplifier is measured, the function generator amplitude U_F shall be set to deliver a sensor response U_S of 50 % to 90 % of the pre-amplifier's saturation point. There is no need to report the setting of U_F since U_F is measured.

e) It is recommended to let the transient recorder show the peak-to-peak voltage of U_S and U_F numerically, as indicated in Figure 5 by the two values marked E and F respectively. This eases to find the coupling situation for the highest SUT response.

f) Vary the coupling quality slightly by moving or turning the SUT and looking at the sensor response, whether it can be improved.

   If the response goes down, refresh the coupling agent between TM and SUT.

g) When the temperature has settled and the coupling is optimal and stable, stop the data capture and store the latest captured data to a properly named file, for example in the following format: "01A-646161.csv", whereby "01" identifies the type of SUT (according to the assignments in the SUT list); "A" identifies TMA as the used transmitter (the serial number of the used transmitters shall be recorded in the transmitter list, see Annex A); "-646161" can represent a string identifying e.g. the serial number of the SUT and/or special conditions of the setup; and ".CSV" indicates the comma separated file format for easy importation into a spread sheet.

h) Remove the SUT from the TM and from the fixing tool and clean SUT, TM and fixing tool from coupling agent.

i) If there are more SUTs to verify, continue with a).

7.4.8 Calculating and presenting receiving sensitivity spectra

The sensitivity spectra are obtained as follows.

a) The data of a SUT captured in a file according to 7.4.7 g), containing the stimulation signal U_F and the sensor response U_S, shall be transformed by FFT to the spectra $F(U_S)$ and $F(U_F)$ and the spectrum R_{SS} calculated according to Formula (4).

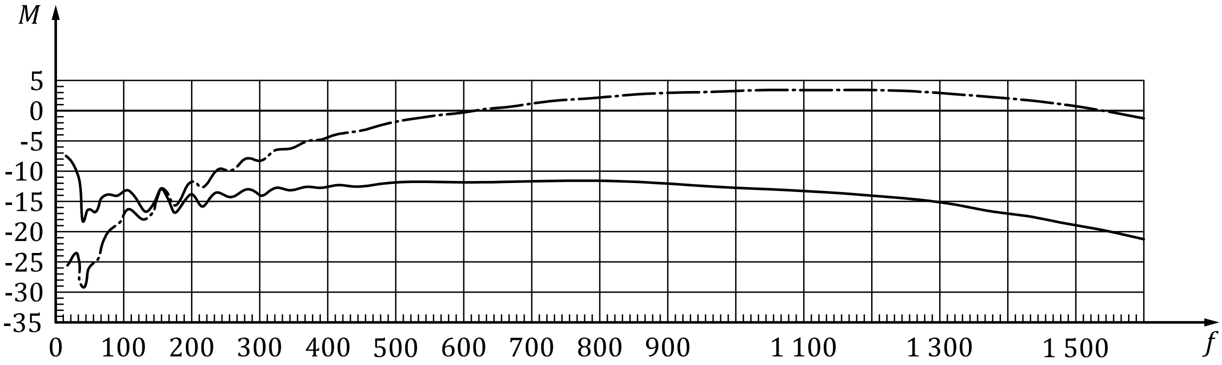
b) For calculation of the sensitivity spectra, the suited transmitting sensitivity spectrum shall be selected according to Table 1, considering the diameter of the SUT's sensitive face and the time window length. For obtaining the transmitting sensitivity spectra see Clause 8 and Annex E.

c) According to Formula (5) the receiving displacement sensitivity is obtained by subtracting the properly selected transmitting sensitivity spectrum (Td) of the used transmitter unit from the signal-to-stimulation ratio spectrum R_{SS} of the used SUT.

d) Figure 5 shows an example representing the receiving sensitivity spectra for the pair of SUT01 and TMA. The selected transmitting sensitivity considered rings 0 to 3 (positions 1 to 13, see Figure 6). A 50 µs long Han2SQ window W7 (see D.2.3) was used. Accordingly, the designation of the selected transmitting sensitivity was "TdA3W7".

Table 1 — Transmitting sensitivity (T_D) to be selected according to the diameter of the sensitive face of the SUT

Diameter of SUT's sensitive face in mm	Considered rings of LVM measurement positions (see Figure 6)	Designation of T_D to be selected (A for TMA) for W7 time window in Clause 4	Designation of T_D to be selected (A for TMA) for W8 time window in Clause 4
< 5,1	0 to 1	TdA1W7	TdA1W8
5,2 to 10,1	0 to 2	TdA2W7	TdA2W8
10,2 to 15,2	0 to 3	TdA3W7	TdA3W8
15,3 to 20,3	0 to 4	TdA4W7	TdA4W8
20,4 to 25,4	0 to 5	TdA5W7	TdA5W8



Key

M magnitude of FFT of receiving displacement sensitivity (R_D) and receiving velocity sensitivity (R_V), in dB

f frequency, in kHz

—·— receiving displacement sensitivity R_D, in dB, with 0 dB referring to 1 V/nm

—— receiving velocity sensitivity (R_V), in dB, with 0 dB referring to 1 Vs/mm

NOTE Conditions: SUT: SUT01-64; Td designation: TdA3W7 for transmitter TMA; rings: 0 to 3; window: W7 (50 µs, Han2SQ)

Figure 5 — Recommended presentation of the receiving sensitivity spectra of a SUT

7.4.9 Sensor verification report

In addition to the graphs, as proposed by Figure 5, the verification report shall include the items listed in Table 2.

Table 2 — Items to be included in the verification report

No.	Item	Report (example)	Acceptable range
1	Used standard	ISO_24543	
2	**Sensor under test** 1_type-Id, 2_type, 3_manufacturer, 4_serial no., 5_no of largest ring (1 to 5) covering the sensitive face, 6_internal discharge resistance in MΩ	1_01, 2_V103, 3_MMM[a] 4_646161, 5_ring 3, 6_none 7_	
3	**Pre-amplifier used** 1_int/ext/none, 2_type, 3_manufacturer, 4_serial no, 5_kind of DC supply, 6_frequency range, 7_amplitude setting at FG for 80 % output range	1_ext, 2_AEP4, 3_ MMM[a], 4_12345, 5_AE system, 6_ (100-1 000) kHz, 7_0,2 V peak	
4	**Transmitter used** 1_Id, 2_type, 3_manufacturer, 4_serial number, 5_last verified (by LVM), 6_temperature at TM face in °C before, 7_after displacement measurement,8_DC blocker used (Y/N) see 6.3 h) and Table A.1, key d	1_A, 2_V104, 3_ MMM[a], 4_ SN1110155, 5_2020-01-10, 6_25,1 °C, 7_25,5 °C, 8_N	
5	Spare		
6	**Function generator** 1_type, 2_manufacturer, 3_serial no, 4_last calibrated	1_33500, 2_ MMM[a], 3_10089, 4_2020-01-10	
7	**Transient recorder** 1_type, 2_manufacturer, 3_serial no., 4_ last calibrated	1_5242A, 2_ MMM[a], 3_10183, 4_2020-02-15	

[a] Replace “MMM” by the name of the manufacturer.

Table 2 *(continued)*

No.	Item	Report (example)	Acceptable range
8	**Coupling agent** 1_type, 2_manufacturer	1_hand milk 2_ MMM[a]	
9	**SUT cable** 1_type of SUT connector, 2_if integral: length in cm, 3_if removable: length in cm	1_Microdot, 2_80 (for e.g. 80 cm integral SUT cable), 3_30 (for e.g. 30 cm removable SUT cable)	2: 20 to 120 3: 20 to 30
10	**Signal cable** from FG to TM and TRA 1_sum of length of two cables in cm	1_120	1: 100 to 150
11	**Crosstalk** 1_initially measured according to 7.4.6	0,2 mV peak	< 1,2 mV peak
12	Spare		
13	**Software used for data analysis** 1_name, 2_release, 3_supplier	1_VST2, R202207/02, 3_MMM[a]	
14	**Original data files** 1_ R_{SS}, 2_T_D	1_S01A-646161 (see Clause 4, line R_{SS}), 2_TdA3W7 (see Table 1, columns 3 and 4)	

[a] Replace “MMM” by the name of the manufacturer.

7.5 Reproducibility of sensitivity spectra

7.5.1 Sensor-to-transmitter coupling

A good and stable sensor coupling quality between the sensor under test and the transmitter is an important requirement for obtaining reproducible sensitivity spectra. For the requirements related to the coupling agent, see 6.5. The proposed face-to-face setup with continuously updated graphs of the sensor response on the PC screen indicates immediately changes in the SUT response (U_S), e.g. when the operator causes changes of the force and/or the direction of the force or small movements between SUT and TM in order to see whether the coupling quality is stable. This helps to achieve well reproducible sensitivity spectra.

7.5.2 Influence of temperature

It is known that both the transmitter’s transmitting sensitivity and the sensor’s receiving sensitivity depend on temperature. This document proposes that the temperature at the transmitter in face-to-face setup be measured and care be taken that it is close to the average of the temperature at the begin and end of the LVM displacement measurement, as reported in Table 2, see 7.4.1 i) and 8.3.1 c).

7.5.3 Change of the transmitter

It emerged that individual units of the chosen transmitter type cause too large a scatter in the sensitivity spectra obtained from the same SUT. Those transmitter units shall not be used for this application. For the criteria to sort out unsuitable transmitters, see 8.5.

8 Determination of the transmitting sensitivity spectra

8.1 Formula for the determination of the transmitting displacement sensitivity

The term transmitting displacement sensitivity (T_D) of a transmitter defines the difference between the output displacement spectrum and the input voltage spectrum, both converted to dB.

In this document, 0 dB of transmitting displacement sensitivity (T_D) refers to 1 nm/V, which equals 1 pm/mV.

Formula (9) defines the determination of the transmitting sensitivity:

$$T_D = F(D) - F(U_L) \tag{9}$$

where

T_D is the transmitting sensitivity spectrum in dB, with 0 dB referring to 1 nm/V, which is equal to 1 pm/mV;

$F(D)$ is the spectrum of the displacement pulse at the transmitter output in dB, with 0 dB referring to 1 pm;

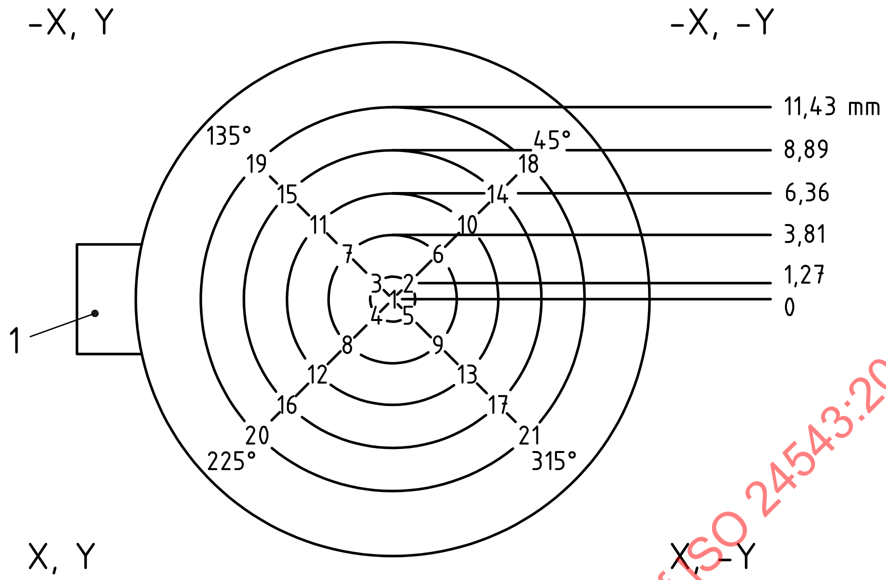
$F(U_L)$ is the spectrum of the stimulation pulse at the transmitter input in dB, with 0 dB referring to 1 mV.

The displacement output D and the transmitting sensitivity T_D are determined in five variants considering five concentric rings of measurement positions around the centre of the active face of the transmitter. This allows the operator to consider that sensitive faces of SUT's of different diameters are stimulated by different patterns of displacement distribution.

The displacement is measured at 21 positions, see Figure 6.

The laser vibrometer setup is used as shown in Figure 1 b).

8.2 Requirements related to the scanning laser vibrometer



Key

1 position of the side connector

NOTE See explanations in 8.2 e).

Figure 6 — Laser vibrometer measurement positions

The following requirements shall be met.

a) A scanning laser vibrometer shall be used for the measurement of both, the voltage pulse driving the transmitter in Volt and the transmitter output motion in nanometres of particle displacement.

The requirements in this clause are tuned to specified characteristics of a commercially available vibrometer product, see B.5.

b) The optical decoder shall cover at least a frequency range from DC to 2,5 MHz (-3 dB) for displacement measurement.

c) The amplitude inaccuracy over frequency of the reference channel shall remain below 0,2 dB up to 250 kHz, below 1 dB up to 2 MHz, and below 3 dB up to 2,5 MHz.

d) The noise over a 2 MHz frequency range shall not exceed 20 pm peak after averaging ten thousand measurements.

The following settings apply.

e) The measurement positions are shown in Figure 6 in small-font numbers 1 to 21, one at the centre point, plus four at each of five concentric rings, plus a 2nd measurement at the centre point, this gives a sequence of 22 measurement positions. The radii of the 5 rings are indicated on the right side of Figure 6. They are calculated according to Formula (10) in millimetres.

$$r_R = N_R \times 2{,}54 - 1{,}27 \quad (10)$$

where

r_R is the radius of ring number N_R in mm;

N_R is the number of a ring in range 1 to 5.

f) Recording time per trigger shall be at least 200 µs (2 000 samples) + pre-trigger time.

g) Averaging of 10 000 records (about 2 048 samples each) per measurement position.

h) Pre-trigger: at least 5 µs for DC-offset determination.

i) The time interval between triggers shall be at least 800 µs for a complete signal decay.

j) The jitter between trigger and displacement signal start shall be less than 50 ns.

For information concerning the calibration of the laser vibrometer see 8.6.

8.3 Procedure for the determination of transmitting sensitivities T_D

8.3.1 Preparation

The following steps shall be performed:

a) Decide on the kind of laser vibrometer to be used. Some of them provide particle velocity measurement only, some in addition particle displacement. This document requires particle displacement measurement.

b) Decide on a scanning laser vibrometer service provider.

c) Prepare for temperature measurement and recording before and after the measurement series for one transmitter.

d) Prepare the positioning unit (Figure 1 b), key 6) for the displacement measurement positions as shown in Figure 6;

e) If a post-amplifier is driving the transmitter, the transmitter voltage (U_L) shall be measured at the post amplifier output, not at the post-amplifier input. This would need a high-impedance voltage divider to avoid saturation of the reference input of the laser vibrometer;

f) To achieve a uniform reflectivity for motion measurement by the laser vibrometer, the active face of the transmitter shall be covered by a mirror foil. Care shall be taken that no air bubble exists between mirror foil and transmitter face.

For an example of a mirror foil, see B.4.

For information concerning the influence of the mirror foil on measurement results, see E.3.

8.3.2 Cable connections for the laser vibrometer setup

Connect the cables as indicated in Figure 1 b).

a) Connect the function generator signal output (key A) to the laser vibrometer reference voltage input (key O) and to the transmitter to be verified (key D) using two coaxial cables and a T-piece.

b) In the case that a DC blocker is required [see 6.3 h) and Table A.1 (key d)], insert it between the cable's end and the transmitter input.

c) Connect the laser vibrometer trigger output (key P) to the trigger input (key C) of the function generator using two coaxial cables and a T-piece.

d) Connect the laser vibrometer (key Q) to the control PC (key M).

8.3.3 Function generator settings for the laser vibrometer setup

The following settings shall be made:

a) Waveform: Sine wave;

b) Frequency: 1 MHz;

c) Amplitude: 10 V peak-to-peak, if no post-amplifier is used;

d) Sweep: off;

e) Burst: on;

f) Start phase: 90°;

g) Trigger: external, if the laser vibrometer triggers the measurement, otherwise: internal;

h) Trigger interval: at least 800 µs to ensure proper signal decay before the next trigger;

i) Polarity: as needed by laser vibrometer controller.

8.3.4 Capturing laser vibrometer data

After consideration of the settings and cabling instructions defined in 8.2 to 8.3.3, proceed as follows.

a) When using a standard function generator with 10 V peak-to-peak maximum amplitude at 50 Ω and a laser vibrometer according to B.5, a series of ten thousand measurements per measurement position shall be averaged for an acceptable signal-to-noise ratio.

b) Perform the laser vibrometer measurements at the foreseen positions and store the calculated average displacement time series signal of each position in a file with a name that contains transmitter id, and measurement position number.

c) Measure the temperature at each transmitter before and after all measurements at a transmitter and report them as T1 and T2 in the transmitter list.

d) The format of the measurement data to be delivered shall be agreed on.

8.3.5 Calculating the displacement results

The following steps shall be performed, usually by a software tool.

a) Measure the DC-offset on basis of the average of the pre-trigger data and subtract it from all samples for offset correction.

b) Eliminate the pre-trigger noise by zeroing all samples before the first main-pulse sample.

c) De-noise the signal data after the main pulse of each measurement position by a Savitzky-Golay filter; recommended parameters are 3rd order, 41 samples. See E.2 for more explanations about displacement measurement.

This results in 22 displacement signals in the time domain.

d) Average the measurement data of four positions per ring, for rings 1 to 5.

e) Calculate the weighted average of the data of rings 0 to N_R, with N_R = 1 to 5, considering that positions at a larger centre distance represent a larger area and shall have accordingly a higher weight.

This results in five displacement signals each 200 µs long. Figure E.2 shows examples of displacement signals.

f) Apply a proper time window length and window function. This document recommends the Han2SQ window of 50 µs and 100 µs length, see D.2.3.

g) Perform fast Fourier transform via an input buffer of 8 K samples, zero-padded, for a frequency resolution of 1,220 7 kHz, for each windowed displacement signal, resulting in 5 displacement spectra per time window.

h) To gain the transmitting sensitivity subtract the voltage spectrum at the transmitter $F(U_L)$ from each displacement spectrum $F(D)$.

   This results in five transmitting sensitivity spectra for five diameters of sensitive faces per time window.

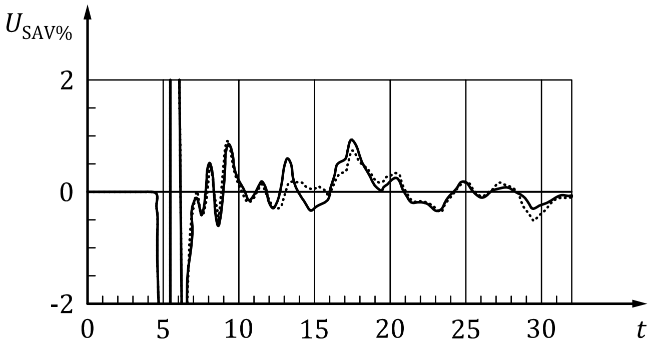
A set of transmitting sensitivity spectra from one transmitter is shown in Figure E.5.

8.4 After completion of the motion measurement

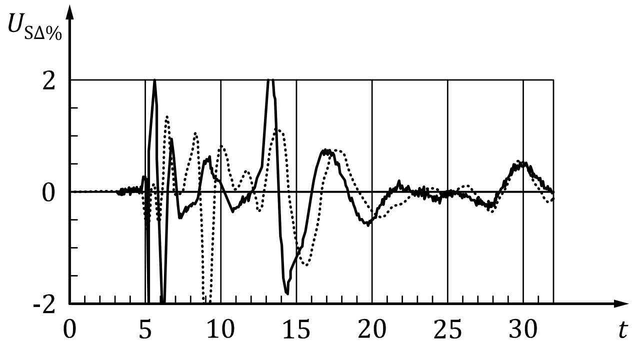
The mirror foil shall be removed from the transmitter completely. Any residues would disturb the results of the measurements in the face-to-face setup.

8.5 Criteria to sort out unsuitable transmitters

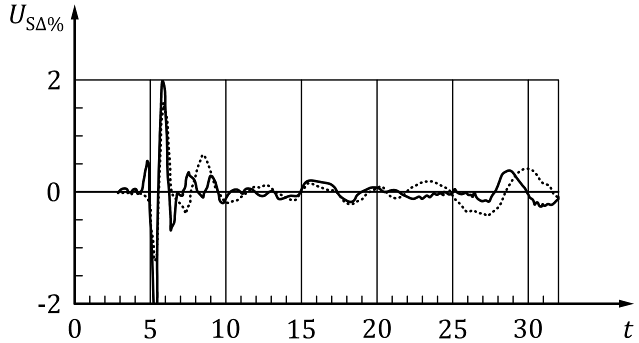
It is recommended to check new transmitters for producing an almost spike-free response of a wide-band sensor during the reverberation phase by using the face-to-face setup, before starting the more expensive determination of the transmitting sensitivity by using the laser vibrometer setup.



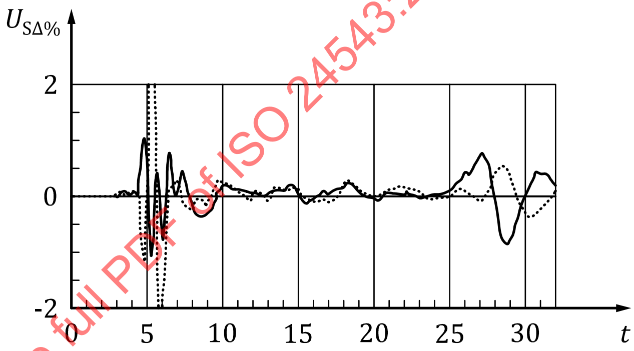
a) Average of U_S, stimulated by 4 and 6 TMs



b) Deviation from average for bad TMB and TMD



c) Deviation from average for better TMA and TMC



d) Deviation from average for better TME and TMF

Key

$U_{SAV\%}$	average of 4 or 6 responses U_S from one SUT, stimulated by 4 or 6 transmitters, in percent of its maximum peak-to-peak voltage
$U_{S\Delta\%}$	deviation of the response U_S, in per cent of its maximum peak-to-peak voltage, from $U_{SAV\%}$ shown in a) by the dotted line
t	time, in µs
______ in a)	average of responses U_S of the six transmitters TMA to TMF
.... in a)	average of responses U_S of the four transmitters TMA, TMC, TME, TMF
______ in b) to d)	deviation of U_S, stimulated by the first transmitter in the caption, in per cent of its maximum peak-to-peak voltage, from the average $U_{SAV\%}$ shown in a) by the dotted line
.... in b) to d)	deviation of U_S, stimulated by the second transmitter in the caption, in per cent of its maximum peak-to-peak voltage, from the average $U_{SAV\%}$ shown in a) by the dotted line

Figure 7 — Deviations from average of SUT01-responses on stimulation by different TMs

Figure 7 a) shows in a solid line the average of six responses U_S of one wide-band sensor (SUT01) to the stimulations by six transmitters TMA to TMF. The vertical scaling is set to indicate the different behaviour of the transmitters during the reverberation phase. The responses are scaled in per cent of their maximum peak-to-peak voltage. The peak voltage of the averaged responses during reverberation at 8 µs to 17 µs in Figure 7 a) is about 0,7 % of the main pulse response. It decays to less than 0,1 % at 32 µs.

The dotted line in Figure 7 a) shows the average of four responses U_S of one wide-band sensor to the stimulations by the four (better) transmitters TMA, TMC, TME and TMF.

Figure 7b) shows the deviations of the responses U_S, stimulated by the bad TMB (solid line) and TMD (dotted line), from the average of four SUT responses shown by the dotted line in Figure 7a).

Figure 7 c) shows the same as b) for the better transmitters TMA (solid line) and TMC (dotted line) and Figure 7 d) shows the same for the transmitters TME (solid line) and TMF (dotted line).

Only the data after 7 µs are of interest.

Figure 7 b) shows spikes far exceeding 1 % between 7 µs and 15 µs, that are not visible in c) and d).

These spikes disqualify transmitters TMB and TMD for the use in the face-to-face setup because the result spectra stimulated by these transmitters would be overlaid by ripple and would differ by several dB from those stimulated by the "better" transmitters.

Among six purchased units of TM are two "bad" ones, four "better" ones and no really "good" one.

A transmitter would be considered "good", if no disturbances would be seen within 50 µs to 100 µs after the stimulation pulse.

Even the "better" transmitters show deviations of the average of up to 1 % starting at about 24 µs, what causes some scatter in the spectra obtained from the same SUT.

There is potential for reducing the scatter, when an optimized "good" transmitter product becomes available.

8.6 Calibration of the laser vibrometer

A laser vibrometer may be calibrated according to ISO 16063-41 in the frequency range 0,4 kHz to 50 kHz.

According to Reference [7], this frequency limitation is due to a lack of adequate vibration exciters for higher frequencies.

This document does not require the performance of a costly calibration according to a standard that does not cover the frequency range used for AE sensor verification.

When using a laser vibrometer model, such as shown in B.5 or of similar construction, the coverage of the frequency range of interest and a much better accuracy than needed is warranted by specifications of the manufacturer, see the explanations in B.5.

8.7 Detection of a drift of a transmitting sensitivity

The trueness of the sensor sensitivity spectrum determined according to 7.4 depends on the trueness of the transmitting sensitivity of the used transmitter sample. This subclause is to help the user to verify if a drift of the transmitting sensitivity occurred, away from that determined according to 8.3.

This subclause recommends assigning the function of a drift detection sensor to two samples of a wide-band sensor model. Both samples should be stored in a safe environment and not used for other purposes. With one drift detection sensor a drift can be discovered but not distinguished whether it is caused by the transmitter or the sensor. With two drift detection sensors a drift of the transmitting sensitivity would cause a drift detection by both sensors. If only one sensor detects a drift, the drift is caused by that sensor and – most probably - not by the transmitter.

a) Every time the transmitting sensitivity of a transmitter is determined according to 8.3, the velocity sensitivities of both drift detection sensors should be determined according to 7.4, and designated “Drift Reference” sensitivities R_{VDR1} and R_{VDR2}.

b) The curves of R_{VDR1} and R_{VDR2} should be verified to be plausibly close.

c) In a certain time period, e.g. every 6 months, or when doubt of validity of the transmitting sensitivity of TMA arises, the drift of the transmitting sensitivity shall be verified as follows.

1) The velocity sensitivity of both drift detection sensors should be determined according to 7.4 and designated “Drift Detection” sensitivities, R_{VDD1} and R_{VDD2}.

2) The difference spectra (R_{VDD1} minus R_{VDR1}) and (R_{VDD2} minus R_{VDR2}) should be calculated and designated $R_{\text{V}\Delta 1}$ and $R_{\text{V}\Delta 2,}$ respectively.

3) In best case, both, $R_{\text{V}\Delta 1}$ and $R_{\text{V}\Delta 2,}$ are close to zero; this indicates that no drift occurred since R_{VDR1} and R_{VDR2} were determined.

4) If both, $R_{\text{V}\Delta 1}$ and $R_{\text{V}\Delta 2}$ show deviations from zero of more than half a dB, this indicates that a drift of the transmitting sensitivity of more than half a dB occurred.

5) It is the decision of the user to have the transmitting sensitivity verified according to 8.3.

Annex A
(informative)

Examples of templates

A.1 Template for a transmitter list

Purpose of this transmitter list is to maintain information about each transmitter in the inventory of an organisation by listing:

a) a unique transmitter identifier (A to Z) along with type, manufacturer and serial number;

b) the date of the last verification using a laser vibrometer setup;

c) the temperature at the ring of the transmitter face measured and recorded before and after the displacement measurements;

d) any relevant comments, for a convenient and consistent transfer of these information into the verification record according to 7.4.9.

An example of a transmitter list template is given in Table A.1.

Table A.1 — Example of a transmitter list

Id	Type	Manu-facturer	Serial no.	Date of last verification	T_1 °C	T_2 °C	SP	d	Comments
A	V104	MMM	1110155	2019-11-13	na	24,0	SA	N	21 and 69 positions
B	V104	MMM	1113009	2020-01-08	24,5	25,0	SA	N	21 positions - DO NOT USE
C	V104	MMM	1165649	2019-11-13	26,8	25,9	SA	N	21 and 69 positions
D	V104	MMM	1162602	2020-01-08	24,0	24,5	SA	N	21 positions - DO NOT USE
E	V104	MMM	1230433	2020-01-08	24,6	25,6	SA	N	21 positions
F	V104	MMM	1230436	2020-01-08	25,9	25,0	SA	N	21 positions
G									
H									
I									
J									
K									

Key

MMM to be replaced by the name of the manufacturer

T_1 Temperature at the ring of the transmitter face before the first displacement measurement

T_2 Temperature at the ring of the transmitter face after the last displacement measurement

SP Code identifying the laser vibrometer service provider

d DC blocker required: Y or N, see 6.3 h)

NOTE The temperatures T_1 and T_2 in line A to F of Table A.1 are above room temperature due to the use of an active antivibration stage. It has been proven that the use of that stage is of no benefit for this application. Future measurements are performed at normal room temperature without the use of the antivibration stage. This avoids the need of a heating tool in face-to-face setup.

A.2 Template for a list of sensor types

Purpose of this list of sensor types is to maintain information about each type of sensor to be verified by listing:

a) a unique SUT type identifier (00 to 99) along with type, manufacturer, optionally a serial number (if the list is used as a SUT list and not as a type of SUT list);

b) the number of the largest ring of measurement positions (N_{RL}) covering the sensitive face, see Figure 6;

c) the sensor internal discharge resistor, see 6.6.2;

d) any relevant comments, for a convenient and consistent transfer of these information into the verification record according to 7.4.9.

An example of a template of a list of sensor types is given in Table A.2.

Table A.2 — Example of a list of sensor types

Id	Type	Manufacturer	Serial no. (optional)	N_{RL}	R_{di} MΩ	Comment
00	V104	MMM	-	5	None	
01	V103	MMM	-	3	None	
02	VS900	MMM	-	3	100	Multi-resonant
03	VS150	MMM	-	3	100	150 kHz resonant
04	VS30	MMM	-	3	100	Low frequency
05	VS45	MMM	-	3	100	Low frequency
06	VS600	MMM	-	2	None	Small
07						
08						
09						
10						

Key

MMM to be replaced by name of manufacturer

N_{RL} Largest ring number of measurement positions (see Figure 6) covering the sensitive face, for correct T_D selection

R_{di} Resistance of sensor internal discharge resistor in MΩ

NOTE The field "Serial no." can also be used to define certain conditions of the setup.

Annex B
(informative)

Examples of equipment

B.1 Example of a function generator

Modell 33220 or 33500, of manufacturer Keysight[1)], fulfil the requirements given in 6.2.

B.2 Example of a transmitter

Modell V104, of manufacturer Olympus[1)], fulfils on principle the requirements given in 6.3, but the uniformity of motion distribution of some samples can cause inacceptable deviations of the sensitivity spectra of a SUT compared to the reference spectra for that SUT. This can be partly solved by selecting suitable samples of that transmitter product, see 8.5.

However, for a better reproducibility of results from different transmitter units, a special transmitter model should be developed and made available.

B.3 Example of a transient recorder

Picoscope USB Oscilloscope Models 5242A[1)] to 5442B[1)].

B.4 Example of a mirror foil

The "Chrom- und Spiegelfolie Artikel-Nr.: 673010[1)]" from Velken Folientechnik, fulfils the requirements given in 6.3 f).

B.5 Example of a scanning laser vibrometer

SmarAct Picoscale Vibrometer[1)] with a F03 sensor head containing a Michelson Interferometer[1)] and a 0,15 NA (numerical aperture) objective for a 7 µm spot radius at focus at 10 mm working distance.

This product uses a distributed feedback (DFB) laser of 1 550 nm wavelength (infrared, for the capability to look through silicon in MEMS applications) that is modulated to obtain a quadrature signal to detect displacements. Both quadrature components are digitized at 16 bit and 40 MS/s and further processed by an advanced algorithm that runs on the field-programmable gate array to output the target displacement at 1 pm resolution and 10 MS/s rate.

The DFB laser is equipped with a thermo-electric cooler (TEC). A feedback loop controls the laser chip temperature such that the wavelength is continuously kept at an absorption line of a gas reference cell that is integrated in the instrument.

Due to the frequency stabilization of the laser source, the linear error of the interferometric measurement is less than 10^{-6} of the measured displacement.

As with any quadrature detection system, small adjustment tolerances can lead to a so-called periodic error.

1) This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.

For the application described in this document, the periodic error is eliminated by averaging 10 000 records per measurement position, see 8.2 g).

Annex C
(informative)

Verification methods for piezoelectric acoustic emission sensors

C.1 General

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 to the active face of a piezoelectric transmitter via a thin layer of coupling agent. The transmitter, usually an ultrasonic probe, stimulates the sensor under test by a particle displacement pulse in normal direction to the sensor's face.

C.2 Early references

Already in 1982, Roger Hill headed in subclause 3.3 of Reference [8] "3.3 Face-to-face calibration" and described the main principle of the face-to-face setup. A sine wave of varied frequency is used for stimulating the pair of transmitter and sensor and as reference for 0 dB sensitivity 1 V/μbar[2)] is introduced on sensitivity charts.

Most sensor manufacturers implemented this principle for the end test of their products and adjusted their internal reference for sensitivity spectra similar to that of the competitors. For certain sensor types, most manufacturers provide similar sensitivity charts.

C.3 Face-to-face setup made available to users

Early 2000 some sensor manufacturers implemented in their AE systems the possibility for the users to obtain sensor sensitivity spectra by the face-to-face method. Only a small investment for a transmitter, a function generator and software is required. By this, the user can easily determine, whether a sensor response is good or bad.

Since different transmitter units produced several dB of scatter in the sensitivity curves, the users were recommended to obtain a sensitivity spectrum from each new sensor, using their own transmitter, for a later comparison, when doubts of aging effects will come up.

It turned out that the face-to-face method generates very well reproducible results, as long as the same transmitter unit is used and no aging effects changed any transmitter property.

C.4 Referring face-to-face results to absolute motion units using laser interferometer

In 2016, K. Ono presented in Reference [9] sensitivity results obtained by the face-to-face method with reference to absolute units of volts per nanometre based on measurements by laser interferometer at the centre point of different transmitters. In addition, Prof. Ono contributed with further publications[10]-[13] to the development of the face-to-face method.

At the world conference on acoustic emission, WCAE 2017, H. Vallen described in Reference [14], a face-to-face setup with sine-wave sweep stimulation, where the transducer motion is measured by a scanning laser vibrometer at 213 points on a rectangular grid on the transducer's active surface. It is shown that

2) 1 μbar = 0,1 Pa.

different transmitter units of the same model exhibit different patterns of motion distribution and that this is the main reason for the scatter in the sensitivity spectra obtained from different transmitters.

At the conference of the European working group on acoustic emission, EWGAE 2018, H. Vallen presented Reference [15], using a specially designed rise of a step function driving a Gaussian-shaped current pulse through the transmitter. That is optimal for particle velocity measurement during the rise of the step function, but the vibrometer response of the exponential decay was buried in noise and the conversion of particle velocity to particle displacement appeared inaccurate.

The face-to-face setup described in this document uses a single-cycle cosine wave as stimulation pulse and a laser vibrometer supporting direct particle displacement measurement at 21 positions at the transmitter's face.

C.5 Existing ISO documents dealing with sensitivity spectrum determination

Presently three ISO documents deal with the determination of the receiving sensitivity of AE sensors:

— ISO 12713:1998 (primary calibration of sensors) is almost a copy of ASTM E1106-86. ASTM E1106 was revised in 2012, confirmed in 2017 and then updated in 2021, but ISO 12713:1998 was never revised.

— ISO 12714:1999 (secondary calibration of sensors) is almost a copy of ASTM E1781-98. E1781 was revised in 2013, but ISO 12714:1999 was never revised.

Both ISO 12714 and ASTM E1781 require a standard sensor calibrated according to ISO 12713 or ASTM E1106. Since the National Institute of Standards and Technology (NIST, USA), the only neutral supplier of calibration service owning a prototype according to ASTM E1106, stopped offering acoustic emission calibration service to external customers, no such standard sensor can be made available to other organizations interested in providing calibration services for sensors. Therefore, the revision of ISO 12714, started in 2016, was cancelled in 2017.

— ISO/TR 13115:2011 (absolute reciprocal calibration of sensors) is an informative Technical Report. To become a normative document, it shall be transferred to an ISO/TS at least. But ISO/TR 13115 is controversially discussed, see Reference [10].

All three mentioned documents require a heavy, immobile transfer block which is impractical for most of the users of acoustic emission systems who need a simple and practical alternative.

Many standards for acoustic emission testing specify a required sensitivity of acoustic emission sensors to be used: Each acoustic emission sensor manufacturer and each acoustic emission service provider shall ensure that the sensors sold and used meet such requirements.

This calls urgently for a practicable and widely accepted sensor verification standard, based on a setup which is easy to use, suitable for practitioners, cost-efficient, and which delivers results of sufficient accuracy and reproducibility, everywhere and by everyone.

This document intends to solve the problems described above. In addition, it is helpful for all users of acoustic emission test systems because it enables an easy and fast verification of the sensitivity of any item in an inventory of acoustic emission sensors.

C.6 Four fundamental problems with primary sensor calibration

NOTE Problems 1 to 3 are described in more detail in Reference [19], Chapter 2, Part 4, Section "Transducer Calibration".

C.6.1 Problem 1

The displacement of a point on the surface of a test block is a three-dimensional vector but the output of the transducer is a scalar.

Reference [19] states in Chapter 2, Part 4, Section "Transducer Calibration": "...It is usually assumed that the transducer is sensitive only to normal displacement. Naturally, errors are introduced if the transducer is sensitive to tangential displacement."

Since Rayleigh waves propagate across the sensor's face, tangential motion components occur at the sensor's face and introduce errors, if the transducer is sensitive to tangential displacement.

In contrast, in a face-to-face setup with pulse stimulation, a 1 µs short dominating plane wave pulse is generated, followed by a radial motion of about 40 dB less amplitude and both are well reproducible.

C.6.2 Problem 2

The displacement at the test object is altered by the presence of the transducer.

Reference [19] states in Chapter 2, Part 4, Section "Transducer Calibration": "...Interaction between the source and load impedances determines the displacement of the transducer face but both of these impedances are likely to be complex functions of frequency and no technique exists for measuring them. For calibration purposes, the usual solution to this problem is to define the input to the transducer as the unloaded (free) displacement of the test block with no transducer attached".

See also Subclause 5.4 of Reference [5], last two sentences: "Since AE sensors are used to monitor motion at a free surface of a structure and interactive effects between sensor and structure are generally of no interest, the free surface motion is the appropriate input variable. It is, therefore, recommended that the units of calibration should be voltage per unit of free motion; for example, volts per metre".

The free displacement at the test block is measured by using a non-contact sensor. The alteration of the displacement due to transducer load is unknown. Hence, the calibration result is only reproducible, if a test block of same geometry and of same positions of source and SUT and same acoustic impedance is used.

C.6.3 Problem 3

Reference [19] page 55: "The face of the transducer covers an area on the surface of the test block and displacement is a function not only of time but also of the position within this area."

Meant is the influence of the aperture effect that depends on the size of the sensitive face but also on the wavelength in the test block.

C.6.4 Problem 4

With a transfer block, the time window from the arrival of the Rayleigh wave via the direct wave path to the arrival of reflections, is very limited.

In subclause 8.3.1 of Reference [5] is specified: "There are also expected errors arising from the fact that data are captured during a finite interval of time (102,4 µs), and any signals from the transducer after this interval are ignored. For transducers which have short ring-down times, this error is expected to be negligible; but to the extent to which there is any ringing in progress at the end of the interval, then there will be significant errors."

Figure 9 and Figure 10 in Reference [5] show that from the first arrival at 25 µs to 102,4 µs, only a time period of 77 µs may be used for the spectrum calculation.

C.7 General advantages of the face-to-face setup

The main advantage of the face-to-face setup is its economic basis, not only due to the use of low-cost instrumentation and the avoidance of a heavy transfer block, but also due to a more simple and fast execution of the verification. A simpler face-to-face method than that proposed is in use with sensor manufacturers for many years. Ten-thousands of AE sensors have been verified using that method.

Concerning the problems mentioned in C.6.1 to C.6.4, these are partly problems for the face-to-face setup, too.

Problem 1 (see C.6.1, errors from lateral/tangential motion sensitivity) is less serious with the face-to-face setup since a dominant particle displacement pulse motion in normal direction to the transmitter's surface is generated by the transmitter during the main pulse. However, a delayed, lower-frequency, radial motion of about 40 dB less amplitude follows the dominant pulse motion and can contribute to errors.

Problem 2 (see C.6.2, displacement alteration due to sensor load) concerns the face-to-face setup in a similar manner. However, recent research concerning the loading effect of transmitters (see Reference [20], page 34) concludes that "damped broad-band ultrasonic transducers were mostly unaffected by the loading effects", this problem 2 seems not to occur in a face-to-face setup.

Problem 3 (see C.6.3, aperture effect) is absent in the face-to-face setup since there are no waves passing across the sensor's face with the exception of the reproducible radial motion of about 40 dB less amplitude compared to the main pulse amplitude.

Problem 4 (see C.6.4, time window limitation) is less critical with the face-to-face setup since no test block is used. However, this document recommends a maximum FFT window of 100 µs after the main pulse in order to reduce scatter in sensitivity spectra obtained, when different transmitter samples are used for stimulation of the same SUT sample.

The face-to-face setup uses a uniform pulse motion distribution across the sensitive face of the sensor under test, from the centre to up to about 12 mm centre distance. Besides the influence of the acoustic impedance on the sensitivity spectrum, there are no influences from the geometry of a transfer block.

More about the influence of the acoustic impedance can be found in Annex F.

The face-to-face results from the active pulse motion are well reproducible, even after disassembling and reassembling of the pair of sensor and transmitter.

The results are easier to understand, and to compare with products of different manufacturers, for the meanwhile large number of practitioners of acoustic emission testing.

C.8 General disadvantages of the face-to-face setup

Since the face-to-face setup results are not influenced by cancellation effects that occur when, for example, a longitudinal wave arrives from another than 90° direction, or when a wave passes across the sensor's face, the sensitivity spectra from face-to-face setup and transfer block setup differ, at least for frequencies above the onset of the aperture effect. The difference grows with the ratio of sensing diameter to wavelength until a maximum is reached and then decreases again.

In addition, the different behaviour of commercially available transmitter units during the reverberation phase, after the active pulse, is still not yet satisfyingly solved.

With the current technology of transmitter manufacture a process to select well behaving transmitter units is recommended, see 8.5.

Annex D
(informative)

Additional information concerning receiving sensitivity determination

D.1 Signal processing in the time domain

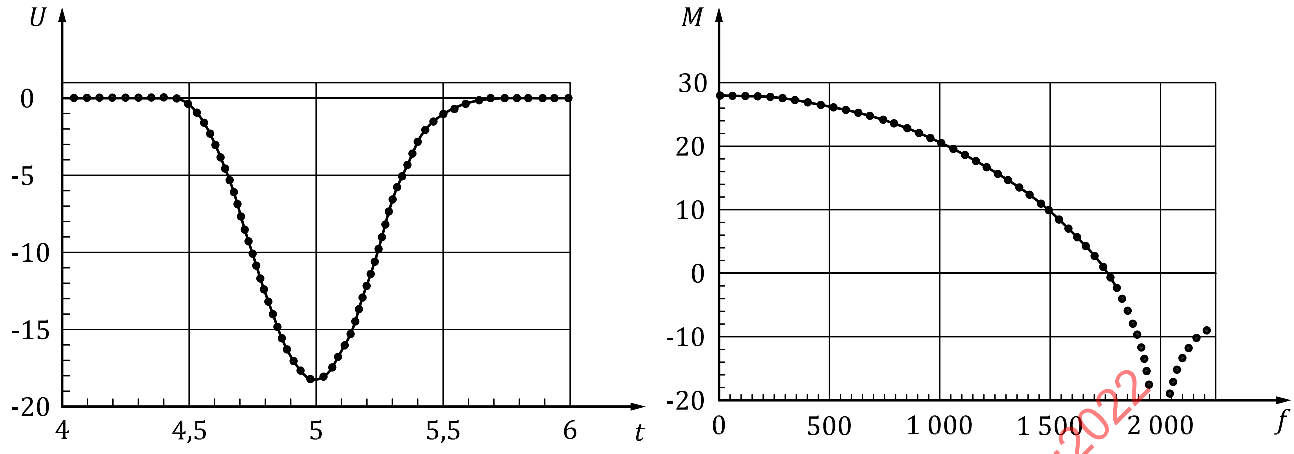
D.1.1 Stimulation pulse

The stimulation signal of a function generator connected to a transmitter generates a particle motion at the transmitter's active face. The stimulation signal can be a continuous sine wave of varying frequency (sweep or steps), or a pulse. When using a rectangular pulse, which contains substantial energies above 2 MHz, artefacts have been encountered, especially when a pre-amplifier of limited bandwidth is part of the measurement chain.

This document recommends the use of a single-cycle sine wave of 1 MHz, starting at 90°. Being at rest, the function generator outputs +10 V. A trigger starts a single 360°-sine-wave cycle from 90° (positive maximum) via 270° (negative maximum) to 450° (next positive maximum). In this way the function generator can drive twice the transmitter current (for twice the displacement), compared to a sine-wave cycle starting at 0°.

The pulse is shown versus time in Figure D.1 a). This shape, when inverted to a positive going pulse, is also called a "cosine wave" or "cosine bell".

In Figure D.1 a) the negative going pulse starts at 0 V due to DC-offset compensation.



a) Stimulation pulse in the time domain

b) Stimulation pulse in the frequency domain

Key

U	signal voltage in V at transmitter TMA
t	time, in µs
M	magnitude of the FFT of the signal in a) in dB, with 0 dB referring to 1 mV peak of a continuous sine wave
f	frequency, in kHz
———	signal acquired at 8 ns sample interval
••••••	signal down-sampled to 25 ns sample interval

Figure D.1 — Stimulation pulse of face-to-face setup in time and frequency domain

For the meaning of the dotted and solid lines see D.1.3.

D.1.2 DC-offset compensation

When using the transient recorder, even in AC input mode, a relatively high DC-offset up to 1 % of the measurement range can be encountered. A DC-offset compensation process is used which averages the first 4,8 µs (600 samples x 8 ns) of pre-trigger data and subtracts this offset from each sample of the captured data.

D.1.3 Down-sampling of time series data of 8 ns to 25 ns sampling interval

The sensitivity spectra obtained is given in same frequency resolution as obtained by the FFT of data sampled in a rate of 5 MS/s, 10 MS/s 20 MS/s or 40 MS/s over a 819,2 µs time period.

Since the selected transient recorder model (see 6.9) supports sample rates of 1 GHz / 2^N only, a sampling rate of 125 MHz (8 ns sampling interval) is used, followed by a down-sampling process which delivers a data stream of 25 ns intervals, corresponding to a 40 MHz sampling rate. This down sampling process first splits up 8 ns intervals into consecutive 1 ns intervals by linear interpolation and then continuously averages 25 consecutive 1 ns intervals to 25 ns intervals.

Figure D.1 a) shows the stimulation pulse in the time domain and Figure D.1 b) in the frequency domain. The continuous lines show the measured signal, the thicker dots the down-sampled signal. Figure D.1 demonstrates that this down-sampling process does not add any remarkable deviation.

D.2 Relevant effects with the fast Fourier transform

D.2.1 Chosen parameters for the FFTs of the face-to-face setup and the laser vibrometer setup

In this document, a 40 MS/s sampling rate for sensor responses and 10 MS/s for displacement signals has been chosen. For a sufficiently fine frequency resolution, a 32 768 samples long zero-extended FFT buffer has been chosen for data sampled at 40 MS/s. The buffer length in time is 819,2 µs. The frequency resolution is the reciprocal value of the buffer time, 1,220 7 kHz. The FFT buffer for 10 MS/s sample rate is 8 192 samples long for 819,2 µs buffer length in time, what leads to the same frequency resolution of 1,220 7 kHz.

D.2.2 Scaling of the FFT results

This subclause explains the relationship between the FFT magnitude and the amplitude in the time domain for the cases of the main pulse in Figure D.1 and of the continuous sine wave in Figure D.2. D.2.3 explains the case of a simulated sine-wave burst signal.

The FFT transforms a signal in the time domain, stored in the FFT input buffer, into the frequency domain in a certain frequency resolution. The FFT result "magnitude" reflects the power distribution of the input signal versus frequency.

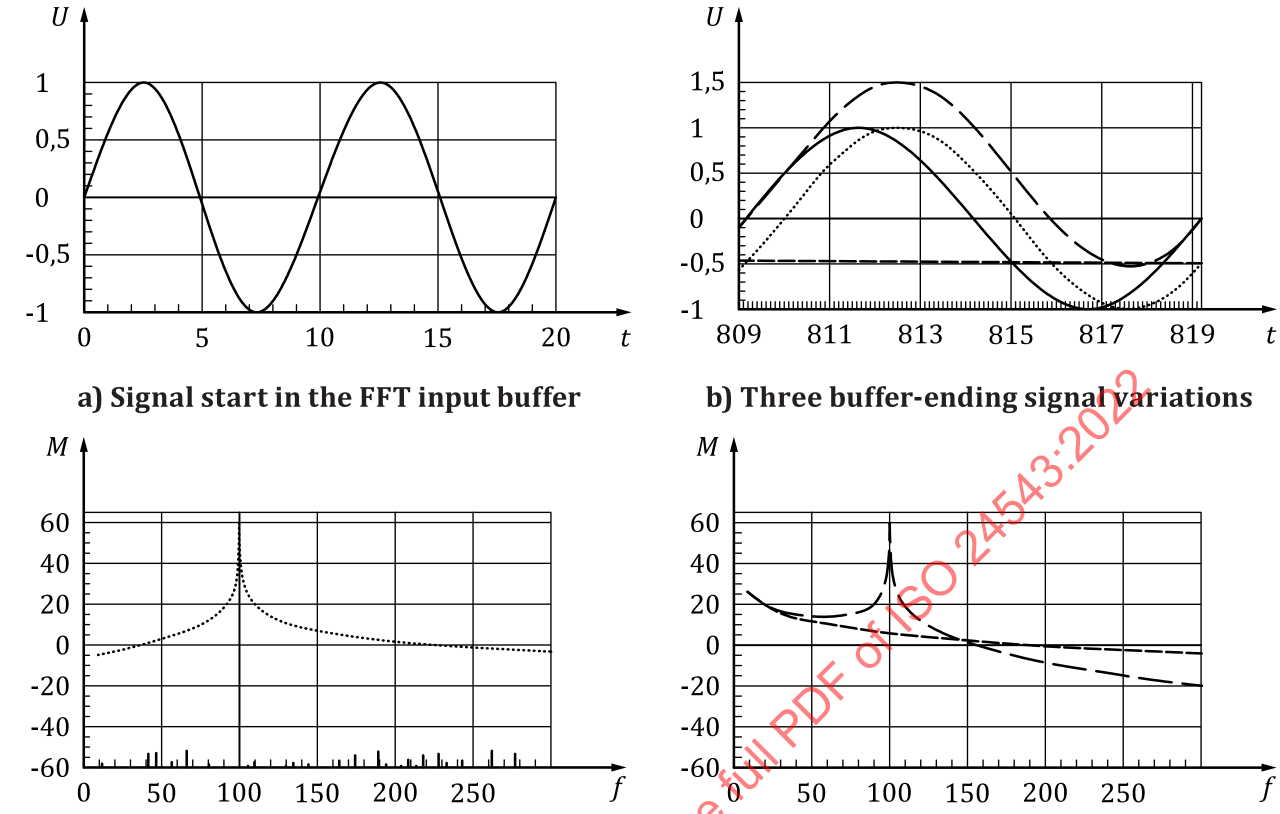
Figure D.1 b) shows the FFT of the signal in Figure D.1 a). The pulse amplitude of 18 V peak would correspond to 85 dB, with 0 dB referring to 1 mV, if the pulse would fill the complete FFT input buffer. Since it fills only about 1,15 µs of the 819,2 µs long FFT buffer, a maximum magnitude of only 28 dB is shown in Figure D.1 b). That magnitude decays by 8 dB at 1 MHz, by 20 dB at 1,6 MHz, by 32 dB at 1,8 MHz, and by about 80 dB (not visible) at 2 MHz. Due to this decay, only spectra up to 1,8 MHz are of interest in this document and only spectra up to 1,6 MHz should be considered "accurate".

Figure D.2 a) shows the first 200 samples of a continuous sine wave in an 8 192 samples long FFT input buffer, sampled in 0,1 µs interval. Figure D.2 b) shows three variants of the signal at the end of the FFT input buffer. The signal amplitude is 1 V peak, the frequency of the solid line in Figure D.2 b) is 100,1 kHz and of the dotted and long-dashed lines it is 100,0 kHz. The solid and long-dashed lines reach zero at 819,2 µs, one sample after the last sample in the FFT input buffer. The FFT algorithm assumes the input buffer represents an endlessly repeating signal, in the time range from 0 to 819,1 µs, where the last sample at 819,1 µs is followed by the first sample at 0 µs. For the FFT, the solid line in Figure D.2 a) and b) is a continuous and step-free sine wave of 100,1 kHz. In contrast, the dotted line exhibits a step from −0,6 V at 819,1 µs to 0 V at 0 µs.

The solid line in Figure D.2 c) shows the spectrum of the (step-free) solid line in Figure D.2 b). All magnitudes are lower than −50 dB, except at 100 kHz, where the magnitude is 60 dB, which corresponds to 1 V peak in time domain.

The dotted line in Figure D.2 c) is the FFT result of the dotted line in Figure D.2 b). It demonstrates the remarkable effect of the step of the dotted line in the time domain on the FFT result: In contrast to the solid line in Figure D.2 c), the dotted line exhibits magnitudes above -20 dB for all frequencies in shown frequency range, caused by the step in the time domain.

The meaning of the short-dashed lines in Figure D.2 b) and Figure D.2 d) is explained in D.2.5.



a) Signal start in the FFT input buffer

b) Three buffer-ending signal variations

c) FFTs of the solid and dotted line in b)

d) FFTs of long- and short-dashed lines in b)

Key

U	signal voltage, in V
t	time, in µs
M	FFT magnitude in dB, with 0 dB referring to 1 mV peak of a continuous sine wave
f	frequency in kHz
———	time domain and FFT of a 100,098 kHz sine wave, reaching zero at buffer end (819,2 µs)
....	time domain and FFT of a 100,0 kHz sine wave, reaching -0,5 V at buffer end, causing a step
– – – –	time domain and FFT of a linear ramp from 0 to the voltage of the dotted line at buffer end
— —	time domain and FFT of a 100 kHz sine wave subtracted by the linear ramp, reaching 0 V at buffer end

Figure D.2 — Continuous sine waves in the time and frequency domain

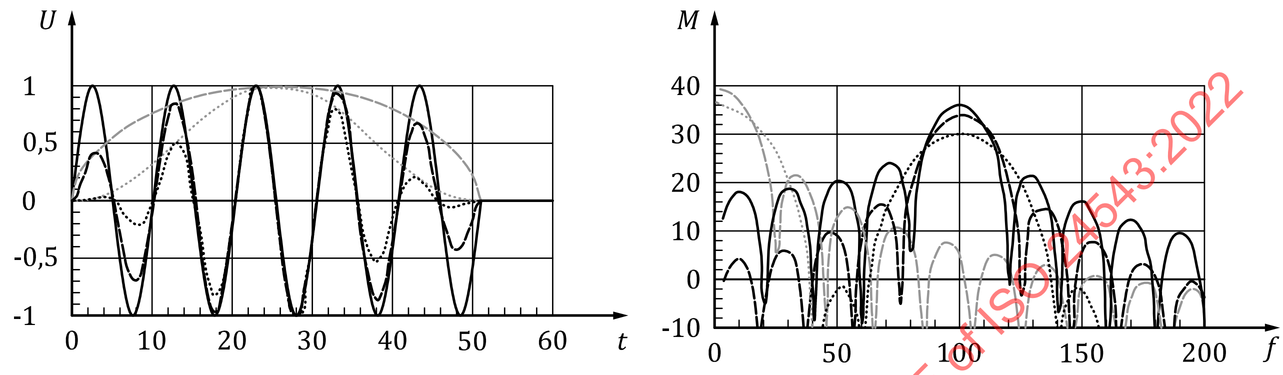
D.2.3 Windowing in the time domain for FFT

The solid line in Figure D.3 a) presents a burst signal of five sine-wave cycles of an amplitude of 1 V peak and 100 kHz frequency at the beginning of the 819,2 µs long zero-padded FFT input buffer. Figure D.3 b) presents the FFT results of the lines in Figure D.3 a) in same line style assignment. The FFT magnitude of the solid line at 100 kHz is lower than 60 dB, compared to Figure D.2 c), because the signal occupies only 50 µs of the 819,2 µs long buffer. 50/819,2 equals 6,1 % or -24,3 dB. 60 dB minus 24,3 dB results in 35,7 dB, the maximum magnitude in Figure D.3 b).

Since the FFT algorithm assumes an endless repetition of the 891,2 µs long input buffer, of which only time 0 µs to 50 µs contain signal parts that differ from 0, as shown in Figure D.3 a), strong side lobes are shown by the solid line in Figure D.3 b) below and above 100 kHz, with maxima and minima about 25 kHz apart. These side lobes stem from the sudden start of the sine wave at 0 µs and the sudden end at 50 µs. Those side lobes can be attenuated by multiplying the time domain signal by a window function, causing a smoother start and end. The grey dotted line in Figure D.3 a) shows a 50 µs long so-called Hanning window function, according to Formula (D.1). The black dotted line in Figure D.3 a) is obtained by multiplying the solid line by the grey dotted line.

Since the average voltage of the black dotted line in Figure D.3 a) is only 50 % of that of the solid line, the FFT magnitude at 100 kHz in Figure D.3 b) of the dotted line is 6 dB below of the solid line.

The black dotted line in Figure D.3 b) contains only two side-lobe peaks of -2 dB at 52 kHz and 148 kHz what demonstrates the attenuation of the side lobes by the application of a window function in the time domain.



a) Sine-wave burst in the time domain

b) Sine-wave burst in the frequency domain

Key

U	signal voltage, in V
t	time, in µs
M	FFT magnitude in dB, with 0 dB referring to 1 mV peak of a continuous sine wave
f	frequency, in kHz
———— (solid black)	burst signal with 5 cycles, 100 kHz, 50 µs duration in a 819,2 µs long zero padded FFT buffer
.... (black dotted)	Hanning window function applied
– – – – – (black dashed)	Han2SQ window function applied
.... (grey dotted)	Hanning window function
– – – – – (grey dashed)	Han2SQ window function

Figure D.3 — Sine-wave burst signal in the time and frequency domain

A 2nd window function, here called Han2SQ, is shown in dashed black and grey lines analogous to the dotted lines. This window function provides less signal attenuation at 100 kHz on cost of less attenuation of the side lobes.

This document recommends the application of the Han2SQ window function on the reverberation phase of all time domain signals to be transformed to frequency domain, see Formulae (D.1) and (D.2).

The formula for the Hanning window function is given in Formula (D.1).

$$U_{\mathrm{H}}[N]=0{,}5\times\left[1+\cos\left(2\times\pi\times\frac{N}{M-1}\right)\right] \quad (D.1)$$

where

U_{H} is the Hanning window function in range 0 to 1;

N is the sample index:

from $-M/2$ to $(M-1)/2$ for windowing the begin and end of a signal as shown in Figure D.3;

from 0 to M-1 for windowing only the end of a signal, e.g. reverberations;

M is the window length in samples, an even number, e.g. 2 000 for a window from N = (0 to 1 999).

The formula for the Han2SQ window function is given in Formula (D.2).

$$U_{\mathrm{H2SQ}}[N] = \mathrm{sqrt}(\mathrm{sqrt}(U_{\mathrm{H}}[N])) \qquad \text{(D.2)}$$

where

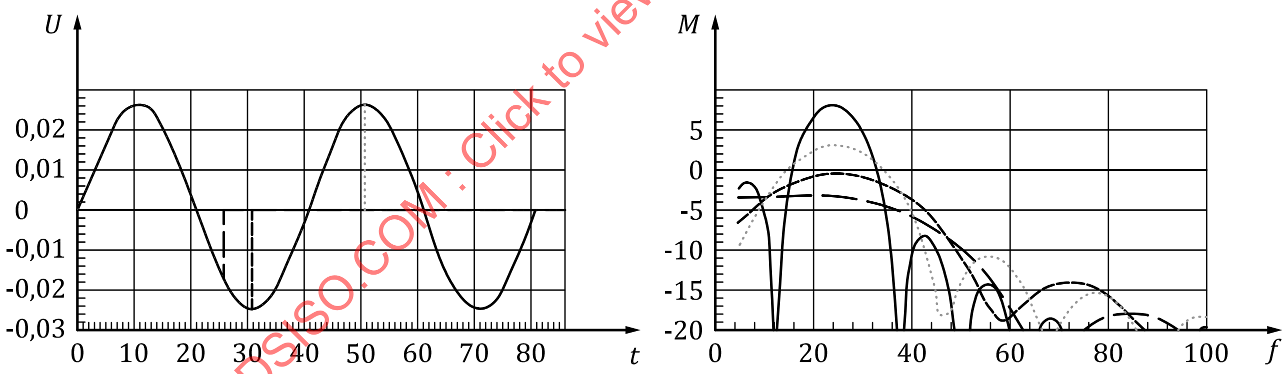
U_{H2SQ} is the Han2SQ window function in range 0 to 1;

sqrt(x) is the square root of x, with x in range 0 to 1.

D.2.4 Frequency discrimination capability at the low-frequency end

This subclause points to the varied sharpness of the amplitude versus frequency information of an FFT result versus the duration of presence of a frequency in the time domain. The frequency resolution in terms of point-to-point interval at the frequency axis of an FFT result is determined by the sampling frequency divided by the number of samples to be processed.

In this document, for the SUT signals (U_{S}) the sampling frequency is 40 MHz, the buffer length is 32 768, this results in a frequency resolution of 1,220 7 kHz. This frequency resolution does not reflect the real capability to distinguish a certain frequency from others.



a) Varied sine-wave presence (time domain)

b) Varied sine-wave presence (FFT)

Key

U	signal voltage, in V
t	time, in µs
M	FFT magnitude in dB with 0 dB corresponding to 1 mV peak of a continuous sine wave
f	frequency in kHz
——— (solid)	25 kHz sine wave from 1 µs to 81 µs
.... (dotted)	25 kHz sine wave from 1 µs to 51 µs
– – – – (short dashes)	25 kHz sine wave from 1 µs to 31 µs
— — — (long dashes)	25 kHz sine wave from 1 µs to 26 µs

Figure D.4 — Frequency discrimination capability versus duration of sine-wave presence

Figure D.4 a) shows a 25 kHz sine wave in four durations of presence as listed in the Key. Figure D.4 b) shows the corresponding FFT results in the corresponding line styles. The 80 µs long presence of the sine wave shown by the solid line leads to a well interpretable maximum of the FFT magnitude at 25 kHz.

The shorter the duration of presence of the sine wave in the time domain, the lower and flatter becomes the maximum of the FFT magnitude. At 25 µs duration of the sine wave, which can be recognized by the return to 0 V of the long-dashed line at 26 µs in Figure D.4 a), the long-dashed line in the FFT indicates only, that a low-frequency component is present, but it is not possible to clearly identify a maximum of magnitude.

The short-dashed lines demonstrate, that a 30 µs presence (75 % of the 40 µs period of 25 kHz) is the minimum duration needed in the time domain to identify the frequency from the maximum of magnitude in the frequency domain.

For reasonable frequency information down to 25 kHz, a 50 µs long time window (1,25 periods) is a minimum.

D.2.5 Considerations to avoid effects from a step in the time domain

If the last sample in an FFT input buffer differs from the first, "spurious frequencies" are introduced.

An early sensor calibration standard (7.5.2 of Reference [5]) defines, with reference to Reference [18], a simple solution to this problem: A linear ramp should be constructed in time domain, from the time and value of the first sample to the time and value of the last sample to be transformed by the FFT. By subtracting the ramp from the signal to be transformed, the step is eliminated. An example is illustrated by Figure D.2 b) and d).

The long-dashed sine wave in Figure D.2 b), ending at 0 V, is obtained by subtracting a linear ramp from the dotted line. The end of the ramp is shown in Figure D.2 b) as a short-dashed line, which equals the dotted line at the last sample.

The step in the dotted line from −0,5 V to 0 V is eliminated in the long-dashed line due to the subtraction of the ramp. Figure D.2 d) shows the FFTs of the long-dashed and short-dashed lines from time 0 µs to 819,2 µs. Even though the step is eliminated in the long-dashed line in time domain, the long-dashed line in the frequency domain does not approach the solid line in Figure D.2 c).

In this example the application of the ramp does not lead to any correction but to an erroneous increase of magnitude at low frequencies by more than 10 dB at 50 kHz and 20 dB at 20 kHz.

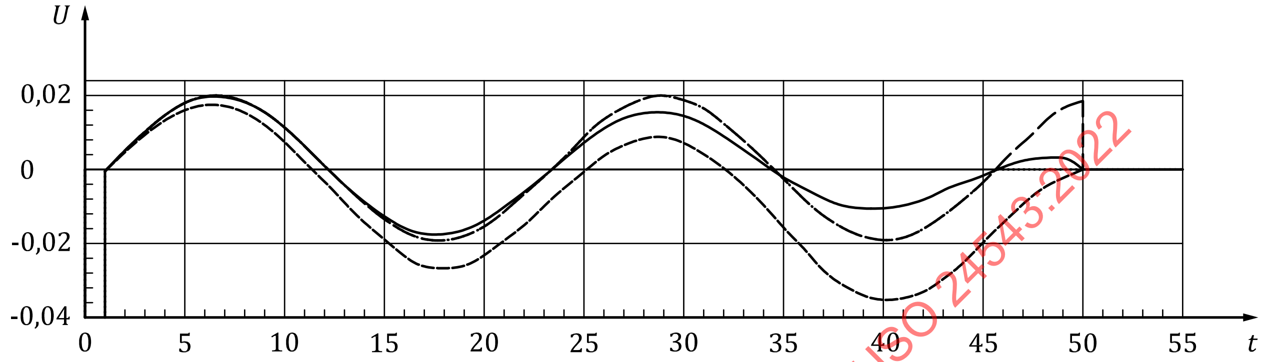
Another example — closer to the signal shapes emerging in the face-to-face setup — is given in Figure D.5. All signals shown in Figure D.5 a) start at 0 µs, 0 V, with a negative-going cosine wave of 1 MHz, (−2 V peak) from time 0 µs to 1 µs, followed by the simulation of a reverberation phase, comprising 2,2 sine-wave cycles of 44,4 kHz frequency from 1 µs to 50 µs (see the long-dashed line ending with a negative-going step at 50 µs).

Approached to real reverberations in the face-to-face setup, the amplitude of the simulated reverberation is 2 % of the amplitude of the initial pulse. The vertical axis of Figure D.5 a) is scaled to visualize the simulated reverberation. From the 2 V peak initial pulse only the begin and the return to 0 V at 1 µs can be seen. The long-dashed line in Figure D.5 a) ends at 50 µs with a step from 0,02 V to 0 V. The dotted line is superimposed on the long-dashed line from 0 µs to 46 µs and remains then at 0 V. The short-dashed line corresponds to the long-dashed line, subtracted by a (non-visible) ramp that connects 0 V at 1 µs with 0,02 V at 50 µs which eliminates the step seen with the long-dashed line at 50 µs. The solid line shows the long-dashed line after application of a 50 µs long Han2SQ-window function starting with value 1,0 at 0 µs.

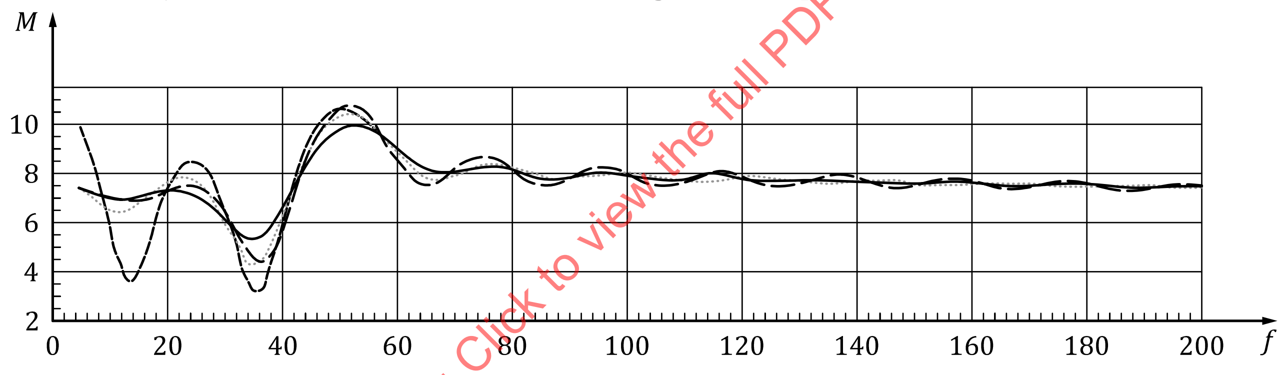
Figure D.5 b) shows the FFTs of the signals in Figure D.5 a), including the initial pulse, in same line style assignment. Figure D.5 c) is a magnitude zoom of Figure D.5 b). The cleanest spectrum is expected from the dotted line in Figure D.5a), since it ends at 46 µs at 0 V without a step. However, the cleanest spectrum below 40 kHz and above 60 kHz is shown by the solid line, which results from Han2SQ windowing.

Over all, it seems the Han2SQ window function is a more suitable alternative to the correction of a step by a ramp, for signals that decay with time as given in the face-to-face setup.

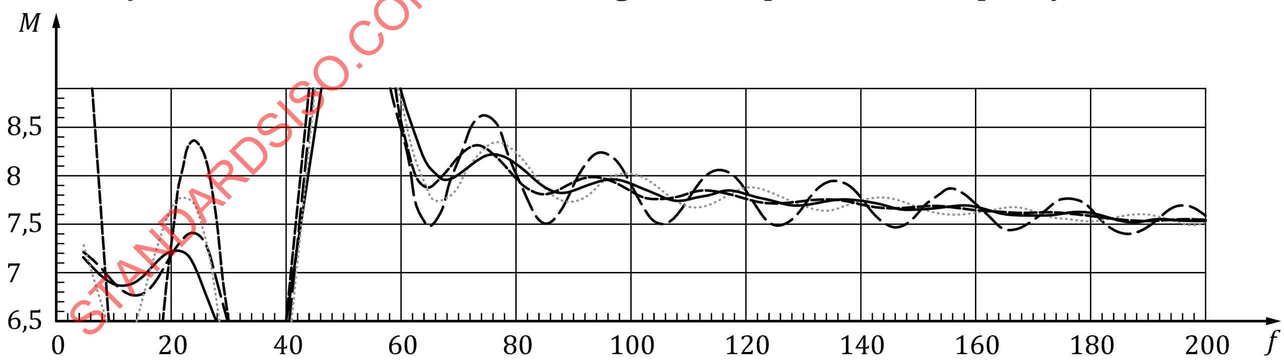
The Han2SQ windowing does not add visible spurious frequencies, as it happens at low frequencies, when a linear ramp is subtracted from the signal in the time domain.



a) Simulated reverberations following the main pulse in the time domain



b) Simulated reverberations following the main pulse in the frequency domain



c) Magnitude zoom of b)

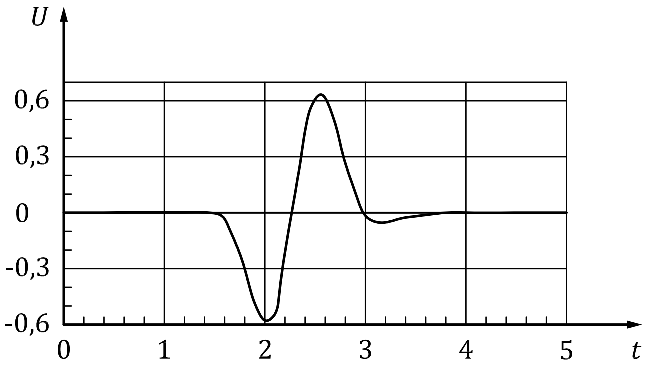
Key

U	signal voltage, in V
t	time, in µs
M	FFT magnitude in dB, with 0 dB referring to 1 mV peak of a continuous sine wave
f	frequency in kHz
———	44,4 kHz sine wave from 1 µs to 50 µs, ending with a step from 19 mV to 0 mV, see a)
········	44,4 kHz sine wave from 1 µs to 46 µs, ending at 0 V after two full cycles, see a)
-----	as long-dashed line, subtracted by a linear ramp to eliminate the step at 50 µs, see a)
— — —	as solid line, with a Han2SQ window function applied to eliminate the step at 50 µs, see a)

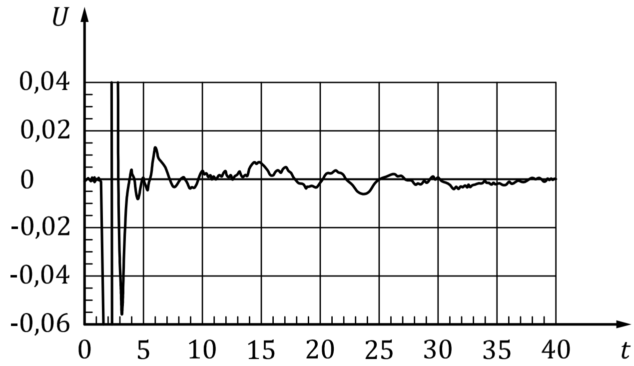
Figure D.5 — Simulated low-frequency low-amplitude reverberations following a main pulse

D.3 Examples of sensor responses and sensitivities of different sensor types

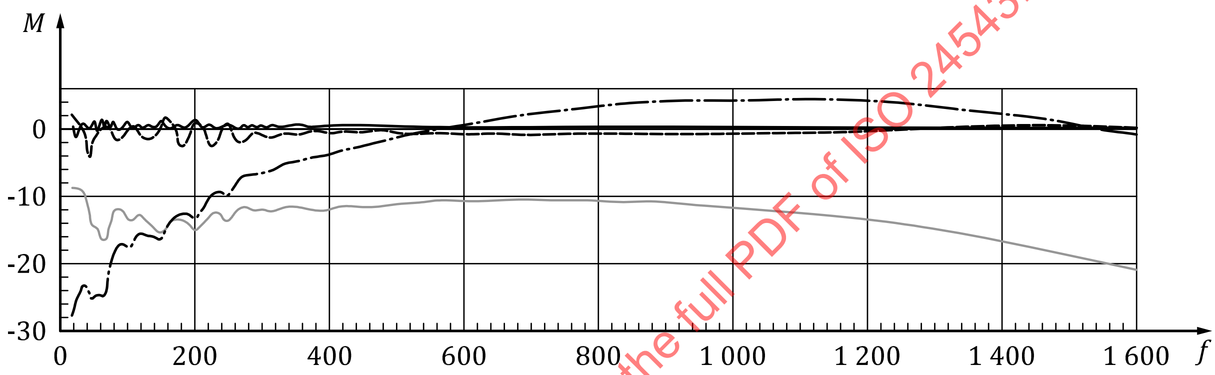
D.3.1 Response and sensitivity of SUT01 (wide band)



a) SUT01 wide-band sensor output, normal scale



b) Vertical zoom of a)



c) SUT01 sensitivity spectra in dB

Key

U	signal voltage, in V
t	time, in µs
M	magnitude in dB
f	frequency, in kHz
—·— in c)	displacement sensitivity R_D, in dB, with 0 dB referring to 1 V/nm, window W7 (50 µs) applied
—— (grey) in c)	velocity sensitivity R_V, in dB, with 0 dB referring to 1 Vs/mm, window W7 (50 µs) applied
- - - - - in c)	difference of R_D when SUT is stimulated by TMA instead of TMC, window W7 (50 µs) applied
—— in c)	difference of R_D when window W8 (100 µs) is used instead of window W7 (50 µs)

NOTE Transmitter is TMC, wide-band SUT is SUT01-64.

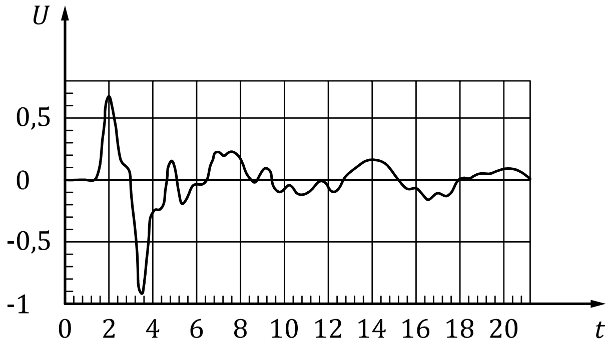
Figure D.6 — Sensor response and sensitivity spectra of wide-band SUT01

Figure D.6 shows the response of a wide-band sensor in the time and frequency domain. The response in Figure D.6 a) is smooth and short and indicates a maximum amplitude of about 1,2 V peak-to-peak. Figure D.6 b) shows in zoomed amplitude scaling the low-amplitude reverberations of about 2 % of the main pulse amplitude. Even though the amplitude of the reverberations is low, in Figure D.6 c) the influence on the sensitivity spectra, the ripples below 300 kHz, is remarkably.

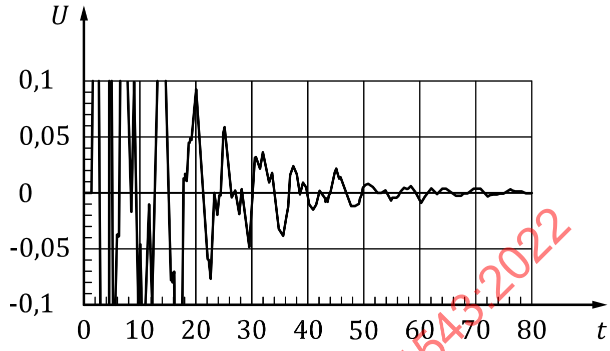
The window function used is Han2SQ, see Formula (D.2), of 50 µs length. In Figure D.6 c), the solid line close to 0 dB indicates the difference in the sensitivity spectra obtained, if the 50 µs long window would be prolonged to 100 µs. Since this line is very close to 0, the longer window would not contribute with more spectral information but with more noise and with the risk of influences contributed by transmitter-individual reverberation properties, which can cause scatter in the sensitivity spectra of a SUT, when stimulated by different transmitter units.

The dashed line close to zero indicates the difference in the sensitivity spectra obtained, if transmitter TMA had stimulated the SUT instead of TMC.

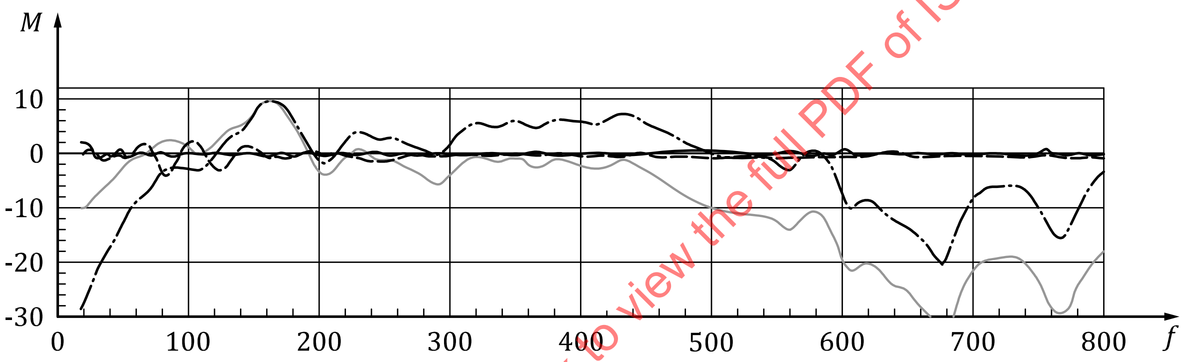
D.3.2 Response and sensitivity of SUT03 (150 kHz narrow band)



a) SUT03 narrow-band sensor output, normal scale



b) Vertical zoom of a)



c) SUT03 sensitivity spectra in dB

Key

U	signal voltage, in V
t	time, in µs
M	magnitude, in dB
f	frequency, in kHz
—.— in c)	displacement sensitivity R_D, in dB, with 0 dB referring to 1 V/nm, window W7 (50 µs) applied
——— in c) (grey)	velocity sensitivity R_V, in dB, with 0 dB referring to 1 Vs/mm, window W7 (50 µs) applied
– – – – in c)	difference of R_D when SUT is stimulated by TMA instead of TMC, window W7 (50 µs) applied
——— in c)	difference of R_D when window W8 (100 µs) is used instead of window W7 (50 µs)

NOTE Transmitter is TMC, SUT is narrow-band 150 kHz SUT03-637.

Figure D.7 — Response and sensitivity spectra of narrow-band (150 kHz) sensor SUT03

Figure D.7 shows the response of a narrow-band sensor in the time and frequency domain.

The main response in Figure D.7 a) is about 1,6 V peak-to-peak, the reverberations about 0,2 V peak-to-peak. Peaks at about 7 µs, 14 µs and 20 µs can be seen what indicates a reverberation frequency of about 150 kHz.

Figure D.7 b) is a vertical zoom of a). The decay time to < 2 % of main response (0,032 V peak-to-peak) is about 50 µs.