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Methods for the calibration of vibration and shock transducers —

Part 22:
Shock calibration by comparison to a reference transducer

Méthodes pour l'étalonnage des transducteurs de vibrations et de chocs —

Partie 22: Étalonnage de chocs par comparaison à un transducteur de référence

Reference number
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Contents

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16063-22 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 3, *Use and calibration of vibration and shock measuring instruments*.

This first edition cancels and replaces ISO 5347-4:1993, which has been technically revised.

ISO 16063 consists of the following parts, under the general title *Methods for the calibration of vibration and shock transducers*:

- *Part 1: Basic concepts*
- *Part 11: Primary vibration calibration by laser interferometry*
- *Part 12: Primary vibration calibration by the reciprocity method*
- *Part 13: Primary shock calibration using laser interferometry*
- *Part 15: Primary angular vibration calibration by laser interferometry*
- *Part 21: Vibration calibration by comparison to a reference transducer*
- *Part 22: Shock calibration by comparison to a reference transducer*

Methods for the calibration of vibration and shock transducers —

Part 22: Shock calibration by comparison to a reference transducer

1 Scope

This part of ISO 16063 specifies the instrumentation and procedures to be used for secondary shock calibration of rectilinear transducers, using a reference acceleration, velocity or force measurement for the time-dependent shock. The methods are applicable in a shock pulse duration range[1] of 0,05 ms to 8,0 ms, and a dynamic range (peak value) of 100 m/s^2 to 100 km/s^2 (time-dependent). The methods allow the transducer shock sensitivity (i.e. the relationship between the peak values of the transducer output quantity and the acceleration) to be obtained.

These methods are not intended for the calibration of dynamic force transducers used in modal analysis.

NOTE 1 This part of ISO 16063 is aimed at users engaged in shock measurements requiring traceability as stated in ISO 9001 and ISO/IEC 17025.

NOTE 2 The methods specified in this part of ISO 16063 are based on the measurement of the time history of the acceleration. These methods fundamentally deviate from another shock calibration method that is based on the principle of the change in velocity, described in ISO 16063-1. The shock sensitivity therefore differs fundamentally from the shock calibration factor obtained by the latter method, but is in compliance with the shock sensitivity stated in ISO 16063-13.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Vibration and shock — Vocabulary*

ISO 5347-22, *Methods for the calibration of vibration and shock pick-ups — Part 22: Accelerometer resonance testing — General methods*[2]

ISO 16063-1:1998, *Methods for the calibration of vibration and shock transducers — Part 1: Basic concepts*

ISO 18431-2, *Mechanical vibration and shock — Signal processing — Part 2: Time domain windows for Fourier Transform analysis*

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1) In exceptional cases, shorter or longer shock pulse durations are possible.

2) Under revision to become a part of ISO 16063.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and the following apply.

3.1
peak value
maximum value of the magnitude or absolute value of the shock pulse

4 Uncertainty of measurement

The limits of the uncertainty of shock sensitivity measurement are as shown in Table 1.

Table 1 — Uncertainty reference conditions for secondary shock calibration

Shock calibrator apparatus	Acceleration peak magnitude[a] km/s^2	Minimum pulse duration[a,b] ms	Uncertainty limit
Pendulum	1,5	3	5 %
Dropball	100	0,100	5 %
Pneumatically operated piston	100	0,100	5 %
Hopkinson bar with velocity comparison	100[c]	0,050[c]	10 %
Hopkinson bar with acceleration comparison	100[c]	0,050[c]	6 %
Split Hopkinson bar with force comparison	100[c]	0,050[c]	10 %

[a] Variations in peak values and duration = ±10 %.

[b] Pulse duration is measured at 10 % of the peak value (see Clause 7).

[c] Larger accelerations (peak values) and shorter pulse durations are possible but without reference to primary methodologies.

The uncertainty of measurement is expressed as the expanded relative measurement uncertainty in accordance with ISO 16063-1 (briefly referred to as “uncertainty”). The specified uncertainties are based on a coverage factor $k = 2$ that is a coverage probability of about 95 %.

The uncertainty specifications of Table 1 can be achieved as long as the spectral energy produced by the excitation of any mode of resonance inherent in the transducer or shock machine structure during calibration is small relative to the spectral energy contained in the frequency range of calibration. The transducer resonance testing shall be performed in accordance with ISO 5347-22.

NOTE For the calibration of transducers of high accuracy (e.g. reference transducers) and if great care is taken to keep all uncertainty components small enough to comply with the specifications (see uncertainty budgets in Annex A), smaller uncertainties than stated in Table 1 may be achievable. For the pendulum shock calibrator, the dropball shock calibrator and the pneumatically operated piston shock calibrator, an uncertainty of 1 % has been obtained in an interlaboratory comparison covering acceleration peak values from 200 m/s^2 to 2 000 m/s^2 [1].

The acceleration peak magnitude may be expressed in terms of the standard acceleration due to gravity, symbol g_n (1 g_n = 9,806 65 m/s^2; 1,5 km/s^2 ≈ 150 g_n).

The shortest shock duration applicable to a transducer according to the manufacturer’s specification shall be taken into account to avoid increasing the measurement uncertainty and damaging or destroying the transducer.

5 Apparatus

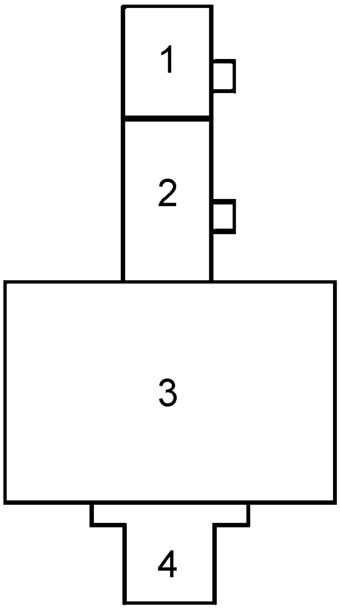
5.1 General considerations

All surfaces on which transducers (the reference or the transducer under test) are mounted shall be polished, flat and clean. The surface on which the transducer is to be mounted shall have a roughness value, expressed as the arithmetical mean deviation, Ra, of less than 1 µm. The flatness shall be such that the surface is contained between two parallel planes 5 µm apart, over the area corresponding to the maximum mounting surface of any transducer to be calibrated. The drilled and tapped hole for connecting the transducer shall have a perpendicularity tolerance to the surface of less than 10 µm; i.e. the centreline of the hole shall be contained in a cylindrical zone of 10 µm diameter and a height equal to the hole depth. Appropriate screw and bolt torque may be found in numerous references and are chosen according to the mounting surface material. The recommendations of the transducer manufacturer shall be followed in all cases.

5.2 Anvil shock calibrators (100 m/s^2 to 100 km/s^2)

5.2.1 General considerations

This clause gives recommended specifications for the anvil shock calibrators to obtain the uncertainties of Clause 4. When back-to-back calibrations are performed with the dropball shock calibrator or the pneumatically operated piston shock calibrator, it is recommended that the transducer under test be mounted directly on top of the reference transducer as shown in Figure 1. This mounting is not recommended for pendulum shock calibrators, see 5.2.2 and Figure 3. For best accuracy, test transducers and mounting fixtures should not have dimensions or masses significantly greater than that of the reference transducer because the sensitivity and frequency response of the reference transducer will vary slightly depending on the amount of mass attached. For all methods, the natural period of the test transducer, equal to the inverse of the resonance frequency, shall be less than 0,2 times the half-sine pulse duration of the applied shock pulse to eliminate excessive overshoot and “ringing” due to resonance excitation.



Key

1 test transducer

2 reference transducer

3 test mass

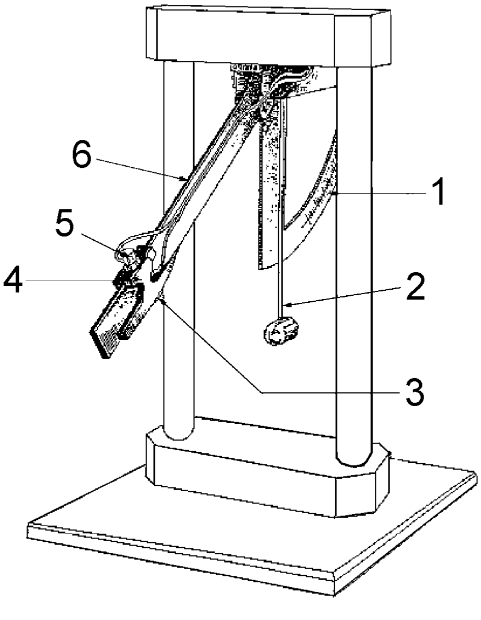
4 anvil

Figure 1 — Recommended mounting of transducers, anvil and test masses

5.2.2 Pendulum shock calibrator

The pendulum shock calibrator provides an assessment of the shock sensitivity and magnitude linearity for transducers and a means of calibrating large quantities of transducers. Comparison calibrations are performed at accelerations ranging from 100 m/s^2 to 1 500 m/s^2 (10 g_n to 150 g_n) at half-sine pulse durations (measured at 10 % magnitude) from 3 ms to 8 ms. A schematic diagram of the pendulum shock calibrator is shown in Figure 2. The shock pulse duration, T, is dependent on the acceleration peak value, i.e. 3 ms at 1 500 m/s^2 and 8 ms at 100 m/s^2. Amplitude linearity may be measured over 4 to 7 impacts of the pendulum system, or with a number of single shock pulses at different acceleration magnitudes.

The pendulum shock calibrator consists of a rigid frame, a hammer pendulum and an anvil pendulum. Typical dimensions for the frame are approximately 500 mm by 500 mm for the square base plate and 780 mm height. The mass of the whole construction is approximately 60 kg. The length of anvil pendulum is approximately 400 mm. Shifting the hammer pendulum to the desired angular displacement and dropping it can excite an impact from the hammer pendulum to the anvil pendulum. An angular scale, graduated in degrees, is provided for determining the angular displacement of the hammer pendulum. The maximum velocity change during the impact phase is less than 3 m/s. A reference transducer and a test transducer are mounted on the pendulum as shown in Figure 3. A scale, graduated in degrees, is provided for angular displacement of the hammer pendulum. Both pendulums have approximately the same moment of inertia to give a series of impacts with decreasing amplitude. A rubber pad between the two pendulums transmits the impact with a known pulse shape from one pendulum to the other. The hardness of the rubber pad determines the pulse shape and duration as well as the number of applicable impacts. To create a haversine pulse shape, typical butadiene rubber pad specifications are 8 mm thickness and 56 Shore A hardness. The test and reference transducers are located at the nodal point for the first axial mode of the anvil pendulum to prevent structural vibrations from contaminating the data. It is recommended that the centre of gravity for the seismic mass of the transducer under test be aligned with the sensitive axis of the reference transducer at the anvil pendulum by means of a mounting stud or other optional mounting adapters [15].



Key

1 graduated scale with adjustable end stop

2 hammer pendulum

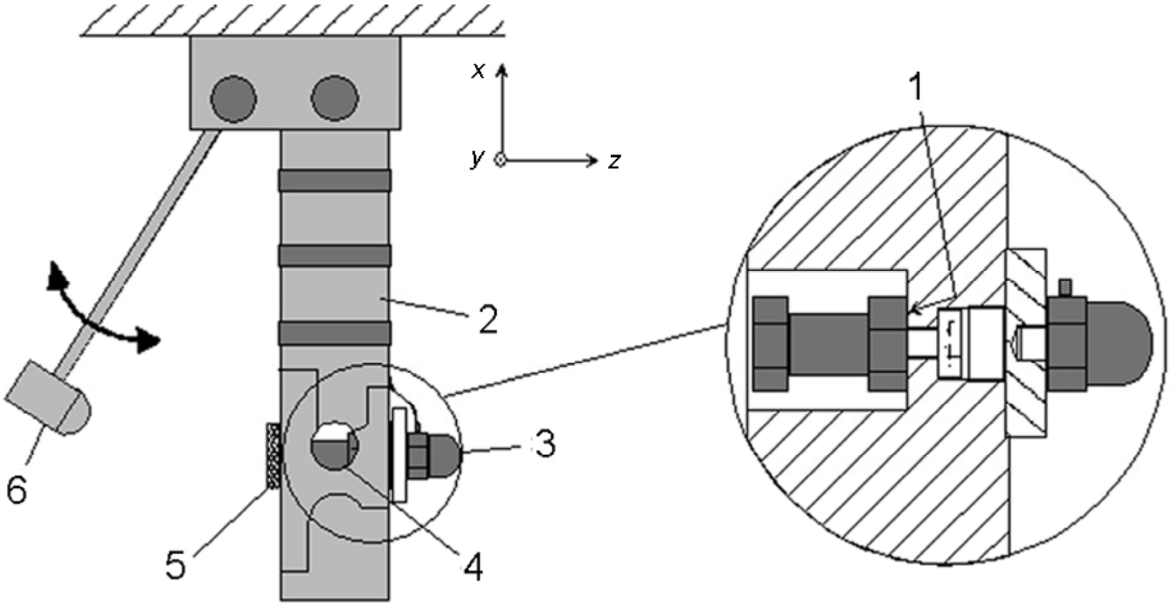
3 rubber pad

4 reference transducer

5 test transducer

6 anvil pendulum

Figure 2 — Example of a pendulum shock calibrator for transducer



Key

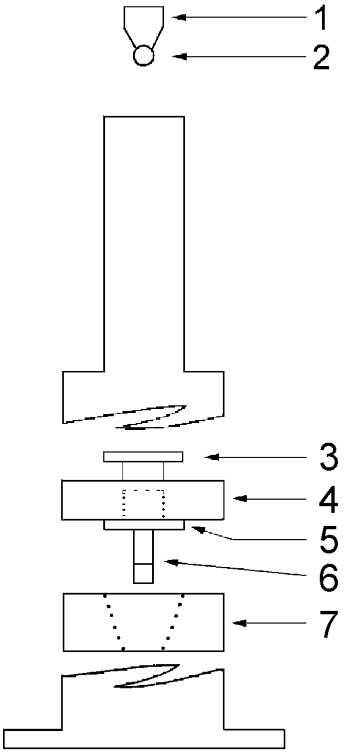
1	reference and measurement surface used for primary calibration
2	anvil pendulum
3	test transducer
4	reference transducer
5	butadiene rubber
6	hammer pendulum

Figure 3 — Correct mounting of transducers and selection of the reference surface for the reference transducer for pendulum shock calibrator

5.2.3 Dropball shock calibrator

A dropball shock calibrator uses a reference transducer mounted back-to-back with the test transducer on a steel anvil as shown in Figure 4. Shock peak magnitudes of 100 m/s^2 to 100 km/s^2 with pulse durations of 0,100 ms to 10 ms are created with the dropball. The assembly is inserted inside the tube of the dropball apparatus with the transducers located on the bottom of the anvil. The anvil is held in place inside the tube magnetically. A vacuum chuck is used to position and release a steel ball bearing located on the top of the tube of the dropball apparatus, such that the ball strikes the centre of the anvil located inside the tube upon impact. Upon impacting the anvil, the ball creates a mechanical shock pulse and causes the anvil to fall freely into a foam rubber catch mechanism located below the magnetic chuck inside the tube of the calibration apparatus. The peak amplitude and duration of the shock pulse created by this collision can be controlled by varying the diameter and mass of the ball[2], and by varying the amount of damping provided by the material added to the impact surface of the anvil.

The dropball apparatus is used to determine sensitivity as a function of either the peak acceleration magnitude (g_{n}) or frequency[3]. Ideally, parameters should be varied to produce pulses that result in significant spectral energy in the frequency range of 5 kHz to 10 kHz, independent of peak amplitude. For example, the diameter of the anvils that produce pulses having peak acceleration amplitudes in the range of 100 g_{n} to 1 000 g_{n} is less than 25 mm. The purpose of the plunger is to prevent multiple collisions of the relatively small-diameter balls with the anvil after the initial impact. The use of small balls with a small-sized anvil to produce pulses has two advantages. First, the decrease in the mass of the anvil reduces the risk of damaging the transducers when the anvil impacts the catch mechanism. Secondly, the reduction in the size of the anvil increases the frequencies of its natural modes of resonance. The second factor is important in the determination of peak amplitudes in the time domain, since anvil resonance can significantly modulate the envelope of the mechanical shock pulse[3].



Key

1 vacuum chuck

2 steel ball bearing

3 plunger (optional)

4 magnetic chuck

5 anvil

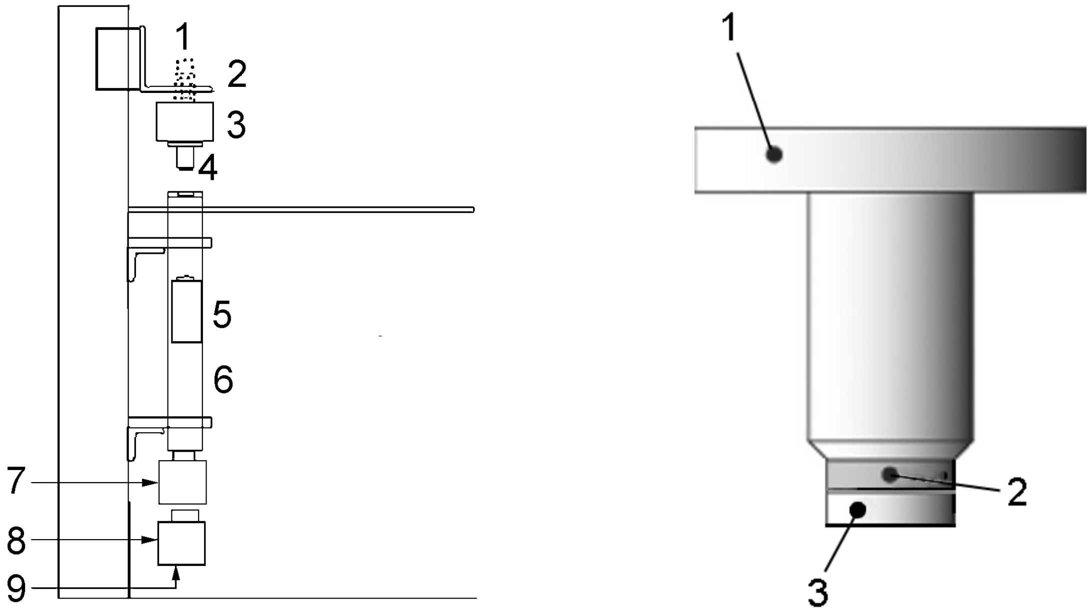
6 transducers

7 catch mechanism

Figure 4 — Example of a dropball shock calibrator for transducer

5.2.4 Pneumatically operated piston shock calibrator

An upward moving pneumatically operated piston provides a simple, controllable and repeatable means of secondary shock calibration of transducers and is shown schematically in Figure 5[4]. Shock peak magnitudes of 200 m/s^2 to 100 km/s^2 (20 g_n to 10 000 g_n) at half-sine pulse durations from 100 µs to 3 ms, respectively, are created by the impact of a steel projectile on an anvil. Typical anvil materials are steel and aluminium. A reference transducer and a test transducer are mounted back-to-back on the anvil. A pressure regulator controls the pressure on the piston. A valve releases the pressure and provides precise control of the piston. When the impact occurs, the anvil lifts off a rubber mount, flies a short distance, and is stopped by a cushioned restraint. The piston is captive within a barrel. A wide range of pulse amplitudes and durations is created with pressure control and combinations of anvils, additional masses, and pad thickness.



Key

1	cushioned restraint
2	transducer under test and reference transducer
3	optional test mass
4	anvil and pad
5	piston
6	barrel
7	valve
8	pressure regulator
9	pressurized air source

Key

1	anvil
2	rubber pad
3	felt pad

a) Shock calibrator

b) Anvil and pad

Figure 5 — Schematic diagram for an upwardly moving pneumatically operated piston shock calibrator

Pads may be torn by high projectile velocity and large additional masses. Damaged pads create non-repeatable pulses and potentially, excessively large amplitudes. Pads shall always be inspected before use. Damaged padding, particularly if it allows metal-to-metal impact between the projectile and anvil, can generate potentially damaging accelerations with nearly any drive pressure.

The characteristics of a shock pulse in general are determined by

a) the velocity of the projectile,

b) the mass of the target (anvil and transducer assembly) and, most critically,

c) the deformation of material between them.

Projectile velocity is approximately proportional to the drive pressure. Anvil velocity (the area under the acceleration curve) is affected by the ratio of the target mass to the projectile mass. Target mass is the sum of the anvil mass, supplemental mass, any additional mounting fixture mass, and the masses of the standard reference and test transducer. The more flexible the material at the point of impact, the longer the duration of the pulse. For a given velocity that results from the impact, the product of the acceleration amplitude and pulse duration is approximately a constant. A thin pad would provide a short high-amplitude pulse, and thicker pad on the same anvil would provide a longer pulse of lower amplitude. The area under the curves of the two pulses would be approximately equal [4].

5.3 Hopkinson bar shock calibrators

5.3.1 General

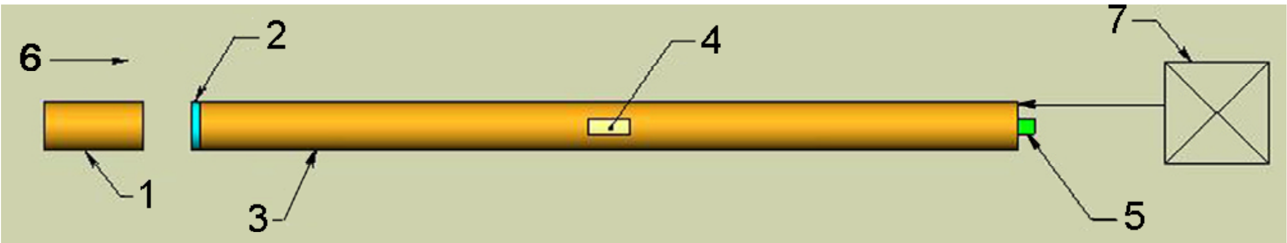
Hopkinson bar shock calibrators have operational ranges of high accelerations (peak values 1 km/s^2 to 2 000 km/s^2) which may be used to evaluate the performance of transducers. This part of ISO 16063 specifies the range from 100 m/s^2 to 100 km/s^2, which has reference to primary methodologies (see ISO 16063-13 for details).

A Hopkinson bar is generally defined as a long slender bar with a length-to-diameter ratio greater than 10. A length-to-diameter ratio of approximately 100 produces excellent results for the methods in this section. A Hopkinson bar calibrator may be instrumented with a reference measurement of either strain gauges or a laser doppler vibrometer (LDV). Either velocity or acceleration comparisons may be made between the reference measurement and the transducer under test. A split Hopkinson bar calibrator compares a reference acceleration derived from a force measurement to the transducer under test. All Hopkinson bar calibrators may be used to evaluate the performance of transducers for peak acceleration values up to 2 000 km/s^2. The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [5,6].

To provide traceability to primary shock standards, a reference transducer calibrated by primary methods shall be used to verify the uncertainty of reference transducers for Hopkinson bar shock calibrators.

5.3.2 Hopkinson bar shock calibrator by comparison in terms of velocity or acceleration

The test transducer may be calibrated in terms of velocity by comparing the integrated output of the transducer with either strain gauges or a laser doppler vibrometer[7, 8]. The test transducer may also be calibrated in terms of acceleration by comparing the output of the transducer with the derivative of the output of either strain gauges or a laser doppler vibrometer[9, 10]. A schematic diagram of the Hopkinson bar shock calibrator is shown in Figure 6. Details of Hopkinson bar calibration with a transfer standard are given in Reference [9].



Key

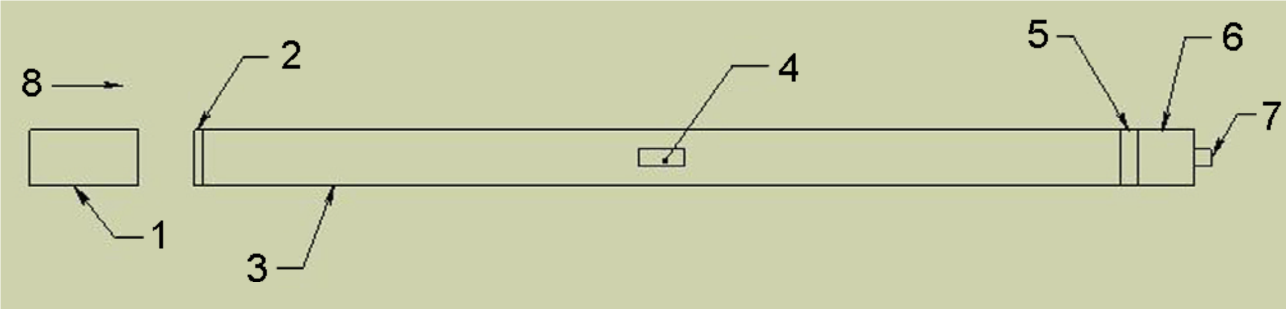
1 projectile
2 pulse shaper
3 Hopkinson bar
4 strain gauge for reference measurement
5 accelerometer being calibrated
6 initial velocity for projectile, v_o
7 laser reference measurement

Figure 6 — Schematic diagram of a Hopkinson bar shock calibrator

5.3.3 Split-Hopkinson bar shock calibrator by comparison with a force transducer

The split-Hopkinson bar calibrator is a comparison of acceleration without integrating the transducer output or taking the derivative of a strain measurement. Figure 7 is a diagram of an aluminium split-Hopkinson bar apparatus with length-to-diameter ratio for the first bar greater than 10[11, 12]. The techniques in 5.3.2[7-10] use the same apparatus, but the transducer is mounted directly to the end of the bar in place of the split configuration. A 0,254 mm thick, 19,0 mm diameter X-cut quartz gauge is bonded to one side of the second bar and the transducer for calibration is on the opposite face of the second bar.

Provided that the rise time of the incident stress pulse created by projectile impact is sufficiently long and the steel disk (second bar) length is sufficiently short, the response of the second bar may be approximated as rigid body motion for steel and tungsten disks[11]. The rigid body acceleration, a, of the steel disk is calculated using the quartz gage force measurement, F, and Newton's Second Law, $F = ma$, where m is the mass of the flyaway with the transducer under test, and compared to the acceleration measured by the transducer under test. A vacuum collar is also used to keep the steel disk in intimate contact with the incident bar. Details of the certification for the split-Hopkinson bar configuration are given in Reference [13].



Key

1	projectile
2	pulse shaper
3	first Hopkinson bar
4	strain gauge for incident wave measurement
5	quartz reference measurement (0,254 mm thick)
6	steel disk or second bar (12,7 mm long)
7	transducer being calibrated
8	initial velocity for projectile, v_{o}

Figure 7 — Example of a split-Hopkinson bar calibrator

5.4 Oscilloscope

An oscilloscope having two or more channels shall be provided for checking the waveforms of the acceleration signals, with a minimum frequency range from d.c. to 1 MHz.

5.5 Waveform recorder with computer interface

A waveform recorder with computer interface capable of analog-to-digital conversion and storage of the two acceleration responses shall be provided. Alternatively, an A/D converter card within the computer may be used. The resolution, the sampling rate and the memory shall be sufficient for calibration in the intended dynamic range with the uncertainty specified in Annex A. A resolution of greater than or equal to 10 bits, preferably 12 bits, is used for the transducer output.

5.6 Computer with data-processing capability

A computer with data-processing programs or an analyser needed by the different shock calibrators used in this part of ISO 16063 shall be provided.

5.7 Filters

Analog filters, applied to the acceleration signals to avoid aliasing and/or to suppress noise, shall have a magnitude and phase response as a function of frequency that is appropriate in order to comply with the tolerable uncertainty of measurement. This requirement shall also be fulfilled for the digital filtering in accordance with the procedures for data processing.

5.8 Other requirements

In order to achieve a small measurement uncertainty in calibration, the transducer and the transducer signal conditioner should preferably be considered as a single transducer and calibrated together. Also, the quartz crystal and the quartz crystal amplifier should be considered as a single transducer and calibrated together.

The transducer shall be structurally rigid. The base strain sensitivity, the transverse sensitivity and the stability of the transducer/amplifier combination shall be taken into account when calculating the uncertainty of measurement.

If a back-to-back reference transducer is calibrated, its sensitivity (magnitude and/or phase lag) shall be measured with a dummy mass that is the equivalent of the mass of the transducer to be calibrated by the comparison method using the back-to-back reference transducer.

6 Ambient conditions

Calibration shall be carried out under the following ambient conditions:

a) room temperature: (23 ± 3) °C;

b) relative humidity: 75 % maximum.

7 Preferred accelerations and pulse durations

The nominal values of acceleration (peak values) and shock pulse duration should preferably be chosen from the following series.

a) **Acceleration**, in metres per second squared:

100, 200, 500, 1 000, 2 000, 5 000, 10 000, 20 000, 50 000, 100 000

b) **Shock pulse duration**,[3] in milliseconds:

0,05; 0,07; 0,1; 0,2; 0,5; 1; 2; 3; 5; 8

NOTE 1 For the acceleration signal generated by a Hopkinson bar shock calibrator, two different shock durations for the positive and negative half-impulse (+10 % and –10 %) may be given.

NOTE 2 If a reference transducer is used, calibrated with a shock machine specified in 4.3 of ISO 16063-13:2001, the shock pulse duration specified in the calibration certificate for the primary shock calibration is related to the entire shock event (Gaussian velocity shape). The shock events corresponding to one another in primary (velocity-based) and comparison calibration (acceleration-based) then have different shock pulse durations (approximately a factor of 2).

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[3] Duration measured at 10 % peak value.

8 Method

8.1 Test procedure

Install the equipment specified in Clause 5.

Before applying a shock, measure any disturbing quantities such as hum and noise. The values shall be sufficiently small to achieve the required uncertainty of calibration. If the output signals from the reference transducer, $u_S(t)$, and test transducer, $u_X(t)$, are electrically filtered, the cut-off frequencies of low-pass filters and, if any, high-pass filters shall be chosen so that disturbing influences from low- and high-pass filtering on the calibration results are tolerable[14].

8.2 Data acquisition

The cut-off frequencies of low-pass filters and, if any, high-pass filters shall be chosen so that disturbing influences from low- and high-pass filtering on the calibration results are tolerable[15]. Data acquisition shall provide sufficiently high resolution, sampling rate and large memory to achieve the required uncertainty. To fulfil Nyquist's theorem, the sampling rate shall be set so that the highest frequency content is lower than half the sampling rate. The output signals from both the reference transducer (u_S) and the transducer to be calibrated (u_X), briefly referred to as test transducer, shall be equidistantly sampled during a measurement period starting shortly before and ending shortly after the mechanical shock event. The sampled series of measurement values denoted $\{u_S(t_i)\}$ and $\{u_X(t_i)\}$ shall be transferred to the computer memory.

The data acquisition should start below or at a time $1 \times T$ before the shock event, and end later or at $1 \times T$ after the shock event, where T is the shock pulse duration as defined in Clause 7. For the Hopkinson bar shock calibrator, the data acquisition interval should be extended until shortly before the reflected pulse occurs.

8.3 Signal processing

8.3.1 General

Examples of methods for data processing to calculate the shock sensitivity as peak value of transducer output to peak value of acceleration are given in 8.3.2 for anvil shock calibrators and in 8.3.3 for Hopkinson bar shock calibrators. Explanations are given in ISO 16063-11, ISO 16063-12 and ISO 16063-13.

8.3.2 Calculation of shock sensitivity for anvil shock calibrators

8.3.2.1 Version 1: Selection of maximum value as peak-value

This version is applicable if the maximum values (max$\{u_S(t_i)\}$ and max$\{u_X(t_i)\}$ of the two series of sampled output signal values represent sufficiently accurately the peak values $\{u_{S,\ peak}\}$, $\{u_{X,\ peak}\}$ after low-pass filtering.

The low-pass filtered output signals should represent a smooth curve with low or no distortion by noise or oscillation due to any resonance (ringing), etc. The ringing may be caused by any resonance in the shock machine or by excitation of the resonance of the reference transducer and/or test transducer by the shock spectrum.

The shock sensitivity of the transducer shall be calculated by data processing as given in the following steps a) to e). The procedure contains digital low-pass filtering described in steps a) and c). These steps may be omitted if the sampled signals are sufficiently smooth.

a) Filter the series of sampled standard transducer output values $\{u_{S,D}(t_i)\}$ using a digital low-pass filter algorithm with parameters suitable for suppressing signal contamination such as ringing and high-frequency noise, without affecting the measurement information. The result is a series of "smooth" signal values $\{u_S(t_i)\}$.

NOTE 1 A filter having maximally flat magnitude response, e.g. a recursive Butterworth low-pass filter of 4th order, is suitable for this purpose provided that compensation is made for nonlinear phase effects.

b) From the series $\{u_S(t_i)\}$ of filtered transducer output values, select the maximum value, max $\{u_S(t_i)\}$, as the peak value $u_{S,peak}$ of the transducer output.

If there is a zero shift in the signal, the zero point immediately before the shock and the shifted zero point immediately after the shock shall be connected by a straight line. This line is the basis for the determination of the output. A maximum zero shift of 1 % relative to the peak value of the output is acceptable. If the zero shift is greater than 1 %, then its effect on the uncertainty of measurement shall be taken into account and the amount of the zero shift shall be reported.

In some shock machines, the signal after the shock is contaminated with resonant response (e.g. ringing). In this case, the zero-point immediately before the shock may be taken as a basis for determination of the output, and the possible effect on the calibration result shall be taken into account in the uncertainty budget.

c) Proceed as in step a) but for the test transducer, with “distorted” output values $\{u_{X,D}(t_i)\}$. The result of filtering is a series of “smooth” values denoted by $\{u_X(t_i)\}$.

d) Proceed as in step b) but for the test transducer. The selected maximum peak value is taken as the $u_{X,peak}$.

e) Calculate the shock sensitivity S_{sh} from the values $u_{S,peak}$, $u_{X,peak}$ obtained in steps b) and d) using the formula with the reference transducer sensitivity, S_S

$$S_{sh} = S_S \frac{u_{X,peak}}{u_{S,peak}} \quad (1)$$

NOTE 2 For simplification, the index X is omitted in the symbol for the sensitivity of the test transducer: $S_{sh} = S_{X,sh}$.

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with Annex A.

If an appropriate two-channel analog filter is applied before sampling the output signals from the transducers, digital filtering according to steps a) and c) may be dispensed with.

8.3.2.2 Version 2: Polynomial approximation (time domain)

This version is applicable if the maximum values (max$\{u_S(t_i)\}$ and max$\{u_X(t_i)\}$) of the two series of sampled output signal values represent sufficiently accurately and directly the peak values $\{u_{S,peak}\}$, $\{u_{X,peak}\}$.

This version is recommended if the sampled output signals from the reference and test transducers, $\{u_S(t_i)\}$ and $\{u_X(t_i)\}$ are distorted by noise or oscillation due to any resonance (ringing), etc., and if no preference is given to digital filtering according to version 1 or to Fourier transform according to version 3.

NOTE Some reasons for preferring version 2 are that the number of sampled values is not sufficient to apply digital filtering for version 1, or that version 3 is too time consuming.

The shock sensitivity of the transducer shall be calculated by data processing in the following steps a) to g).

a) Define an approximation interval around the estimated peak values of the sampled series of the output $\{u_S(t_i)\}$ of the reference transducer.

NOTE From the series $\{u_S(t_i)\}$, select all values that exceed a value $\{u_S(t_i)\} = \alpha \cdot u_{S,peak}$. Preferably, α = 0,9 (first choice) or α = 0,95 is chosen. The selected values form the series $\{u_S(t_i)\}_{app}$ to be approximated.

b) Approximate the series $\{u_S(t_i)\}_{app}$ by an approximation polynomial of second order:

$$u_S(t) = b_{S,2}\, t^2 + b_{S,1}\, t + b_{S,0} \tag{2}$$

Calculate the constants $b_{S,0}$, $b_{S,1}$, $b_{S,2}$ using the Gaussian least-squares method.

c) The peak value $u_{S,peak}$ is obtained from the constants $b_{S,0}$, $b_{S,1}$, $b_{S,2}$ using the formula

$$u_{S,peak} = b_{S,0} - \frac{{b_{S,1}}^2}{4\ b_{S,2}} \tag{3}$$

See 8.3.2.1, step b).

d) Perform step a) for the test transducer, having output values $\{u_X(t_i)\}$. The selected values form the series $\{u_X(t_i)\}_{app}$.

NOTE It may be appropriate to choose another value α than that chosen for the reference transducer.

e) Perform step b) for the test transducer. The constants $b_{X,0}$, $b_{X,1}$, $b_{X,2}$ of the approximation polynomial $u_X(t)$ are obtained.

f) Perform step c) but for the test transducer. The peak value $u_{X,peak}$ of the approximation polynomial is obtained.

g) Calculate the shock sensitivity S_{sh} from the values $u_{S,peak}$, $u_{X,peak}$ obtained in steps c) and f), using Equation (1).

When the calibration results are reported, the expanded uncertainty of measurement in the calibration shall be calculated and reported in accordance with Annex A.

8.3.2.3 Version 3: Sensitivity calculation using FFT analysis

This procedure can be used to calculate

- the complex spectral sensitivity $S(j\omega)$ or magnitude and phase shift of the test transducer, excited by shock acceleration at any peak value, or
- the transducer's shock sensitivity S_{peak} defined by Equation (1).

The procedure is applicable if the complex sensitivity of the reference transducer is known at the frequencies that are relevant for the Fourier spectrum. The complex sensitivity of the reference transducer can be determined by primary shock calibration in accordance with ISO 16063-13:2001, Annex C. If the reference transducer has proved to be linear, the primary shock calibration may be replaced by primary vibration calibration in accordance with ISO 16063-11 or ISO 16063-12, or by secondary complex calibration in accordance with ISO 16063-21.

As no transducer is perfectly linear, the uncertainty contribution due to linearity deviation shall be taken into account in the uncertainty budget.

The complex sensitivity $S(j\omega)$ and the shock sensitivity S_{peak} of the transducer shall be calculated by data processing in the following steps a) to g), and a) to i), respectively.

a) Take m repeat measurements (i.e., k sampled series') $\{u_S(t_i)\}_k$, $\{u_X(t_i)\}_k$, with k = 1, 2,..., m.

NOTE 1 The sampling time period defines the frequency resolution achieved; e.g. 80 ms sampling period leads to a frequency resolution of 12,5 Hz.

b) Perform Fast Fourier Transform (FFT) or Discrete Fourier Transform (DFT) using appropriate windowing. If a rectangular window is used, see ISO 18431-2.

c) Average the data from the repeated measurements in the frequency domain to obtain averaged spectra $u_\text{S}(\text{j}\omega)$ of the reference output signal and $u_\text{X}(\text{j}\omega)$ of the test output signal.

d) Calculate the complex sensitivity $S_\text{X}(\text{j}\omega)$ of the test transducer using the formula

$$S_\text{X}(\text{j}\omega) = S_\text{S}(\text{j}\omega)\frac{u_\text{X}(\text{j}\omega)}{u_\text{S}(\text{j}\omega)} \tag{4}$$

e) Calculate the coherence function γ and check the compliance with the minimum tolerable value.

NOTE The value should lie in the range $\gamma \geqslant 0{,}99$. A lower value is only tolerable if the contribution to the uncertainty of measurement is taken into account.

f) Calculate the spectrum of the complex acceleration

$$a(\text{j}\omega) = \frac{u_\text{S}(\text{j}\omega)}{S_\text{S}(\text{j}\omega)} \tag{5}$$

from the averaged spectrum of the output of the reference transducer and its complex sensitivity, determined as described above.

g) Transfer the averaged spectra $u_\text{X}(\text{j}\omega)$ and $a(\text{j}\omega)$ into the time domain by Inverse Fourier Transform (IFFT or IDFT) to obtain series of instantaneous measurement values of the test transducer output $u_\text{X}(t_\text{i})$ and the associated accelerations $a(t_\text{i})$.

h) From the series $\{u_\text{X}(t_\text{i})\}$ and $\{a(t_\text{i})\}$ obtained in step g), select the maximum values max $\{u_\text{X}(t_\text{i})\}$ and max $\{a(t_\text{i})\}$ considered to represent the peak values $u_\text{X,peak}$ and a_peak.

i) Calculate the shock sensitivity S_sh from the values $u_\text{S,peak}$, a_peak obtained in step h) using the formula

$$S_\text{sh} = \frac{u_\text{X,peak}}{a_\text{peak}} \tag{6}$$

8.3.3 Calculation of shock sensitivity for Hopkinson bar shock calibrators

8.3.3.1 General

Version 1 (8.3.2.1) and version 2 (8.3.2.2) are used to calculate shock sensitivity for Hopkinson bar shock calibrators once the two quantities for comparison are obtained in the same units.

8.3.3.2 Calculation of shock sensitivity for Hopkinson bar shock calibrator with velocity comparison

For this method, the reference measurement from either strain gauges or from a laser doppler vibrometer (LDV) will be in velocity. The acceleration measurement from the transducer under test must be converted from acceleration to velocity by integration. Since integration is a smoothing process, no additional processing is necessary. Either version 1 (8.3.2.1) or version 2 (8.3.2.2) may be used to calculate the shock sensitivity with the substitution of peak velocity values for peak acceleration values.

8.3.3.3 Calculation of shock sensitivity for Hopkinson bar shock calibrator with acceleration comparison

For this method, the reference measurement from either strain gauges or from a laser doppler vibrometer (LDV) will be in velocity and must be converted to acceleration by differentiation. Time-domain or frequency-domain differentiation is acceptable. Generally, low-pass filtering is advisable before and after the differentiation process to eliminate extraneous noise. The cut-off frequency is chosen to be high enough that the frequency bandwidth of interest is not affected by the filtering process. Either version 1 (8.3.2.1) or version 2 (8.3.2.2) may be used to calculate the shock sensitivity with the peak acceleration values.

8.3.3.4 Calculation of shock sensitivity for split-Hopkinson bar shock calibrator with comparison with a force transducer

For this method, the reference measurement is the acceleration obtained by dividing the quartz force measurement by mass that includes the quartz crystal, the steel disk, and the transducer under test. Either version 1 (8.3.2.1) or version 2 (8.3.2.2) may be used to calculate the shock sensitivity with the peak acceleration values.

9 Reporting the calibration results

When the calibration results are reported, in addition to the calibration method at least the following conditions and characteristics shall be stated.

a) Ambient conditions
   - ambient air temperature.

b) Mounting technique
   - material of mounting surface
   - mounting torque (if the transducer is stud-mounted)
   - oil or grease (if used)
   - cable fixing
   - orientation (vertical or horizontal).

c) Dummy mass (if used)
   - material (e.g. steel), dimensions (length, diameter), mass
   - mounting torque.

d) Calibration results
   - peak value and shock pulse duration
   - values of shock sensitivity
   - expanded uncertainty of measurement, k factor.

Annex A
(normative)

Expression of uncertainty of measurement in calibration

A.1 Calculation of the expanded uncertainty, $U_{\mathrm{rel}}\,(S_{\mathrm{sh}})$, for the shock sensitivity, S_{sh}, for given acceleration peak value, shock pulse duration, and settings of amplifier gain and filter cut-off frequencies

The relative expanded uncertainty of measurement of the shock sensitivity, $U_{\mathrm{rel}}\,(S_{\mathrm{sh}})$, for the acceleration peak value, shock pulse duration, and settings of amplifier gain and filter cut-off frequencies shall be calculated in accordance with ISO 16063-1 from the following formulae:

$$U_{\mathrm{rel}}(S_{\mathrm{sh}}) = k u_{\mathrm{c,rel}}(S_{\mathrm{sh}})$$

$$u_{\mathrm{c,rel}}(S_{\mathrm{sh}}) = \frac{u_{\mathrm{c}}(S_{\mathrm{sh}})}{S_{\mathrm{sh}}} = \frac{1}{S_{\mathrm{sh}}}\sqrt{\sum_i u_i^2(S_{\mathrm{sh}})}$$

with the coverage factor $k = 2$. See Table A.1.

The sources of uncertainties may be sub-divided and numbered in a way different from that used in the tables, provided that each effect that significantly influences the measurement result has been taken into account as per of ISO 16063-1:1998, Annex A.

A.2 Calculation of the expanded uncertainty, $U_{\mathrm{rel}}\,(S_{\mathrm{h,t}})$, for the shock sensitivity, $S_{\mathrm{h,t}}$, over the complete range of acceleration peak value and shock pulse duration

The expanded uncertainty of measurement of the shock sensitivity $U_{\mathrm{rel}}\,(S_{\mathrm{sh}})$ is valid only for the calibration peak value, shock pulse duration, and settings of amplifier gain and filter cut-off frequencies at any time during the interval between successive calibrations. The relative expanded uncertainty of measurement of the sensitivity $U_{\mathrm{rel}}\,(S_{\mathrm{sh}})$ for the complete range of acceleration peak value and shock pulse duration, shall be calculated in accordance with ISO 16063-1 from the following formulae:

$$U_{\mathrm{rel}}(S_{\mathrm{sh,t}}) = k u_{\mathrm{c,rel}}\left(S_{\mathrm{sh,t}}\right)$$

$$u_{\mathrm{c,rel}}(S_{\mathrm{sh,t}}) = \frac{u_{\mathrm{c}}(S_{\mathrm{sh,t}})}{S_{\mathrm{sh}}} = \frac{1}{S_{\mathrm{sh}}}\sqrt{\sum_i u_i^2\,(S_{\mathrm{sh,t}})}$$

with the coverage factor $k = 2$. See Table A.2.

The sources of uncertainties may be sub-divided and numbered in a way different from that used in the table, provided that each effect that significantly influences the measurement result has been taken into account as per ISO 16063-1:1998, Annex A.

Table A.1

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(S_{\mathrm{sh,S}})$	Combined standard uncertainty for the reference (transducer or transducer-conditioner combination) at specified conditions	$u_1(S_{\mathrm{sh}})$
2	$u(G)$	Conditioning amplifier gain ratio ($G = G_{\mathrm{S}}/G_{\mathrm{X}}$)	$u_2(S_{\mathrm{sh}})$
3	$u(R_{\mathrm{V}})$	voltage peak value ratio measurement (waveform recorder; e.g. ADC resolution)	$u_3(S_{\mathrm{sh}})$
4	$u(R_{\mathrm{I}})$	reference transducer instability over time	$u_4(S_{\mathrm{sh}})$
5	$u(R_{\mathrm{F}})$	voltage filtering effect on voltage peak value ratio measurement (frequency band limitation)	$u_5(S_{\mathrm{sh}})$
6	$u(R_{\mathrm{VD}})$	effect of voltage disturbance on voltage peak value ratio measurement (e.g. hum and noise)	$u_6(S_{\mathrm{sh}})$
7	$u(R_{\mathrm{T}})$	effect of transverse, rocking and bending acceleration on voltage peak value ratio measurement (transverse sensitivity)	$u_7(S_{\mathrm{sh}})$
8	$u(R_{\mathrm{F}})$	effect of mounting parameters (torque, cable fixing, dummy mass, etc.) on voltage peak value ratio measurement	$u_8(S_{\mathrm{sh}})$
9	$u(R_{\mathrm{VD}})$	effect of temperature and other environmental parameters on voltage peak value ratio measurement	$u_9(S_{\mathrm{sh}})$
10	$u(R_{\mathrm{MD}})$	effect of motion disturbance on voltage peak value ratio measurement (e.g. relative motion between the sensing surfaces of the transducers)	$u_{10}(S_{\mathrm{sh}})$
11	$u(R_{\mathrm{L}})$	effects of nonlinearities on voltage peak value ratio measurement and other residual effects on voltage peak value ratio measurement	$u_{11}(S_{\mathrm{sh}})$
12	$u(S_{\mathrm{sh,RE}})$	residual effects on shock sensitivity measurement (resonance excitation in the transducer or shock machine effects, repeated measurements random effects; standard deviation of arithmetic mean)	$u_{12}(S_{\mathrm{sh}})$

Table A.2

i	**Standard uncertainty component** $u(x_i)$	**Source of uncertainty**	**Uncertainty contribution** $u_i(y)$
1	$u(S_{\mathrm{sh}})$	uncertainty of shock sensitivity calculated at reference peak value, shock pulse duration and amplifier gain settings in accordance with ISO 16063-1:1998, A.1.1.	$u_1(S_{\mathrm{sh,t}})$
2	$u(e_{\mathrm{T,A}})$	conditioning amplifier tracking (deviations in gain and phase shift for different amplification settings)	$u_2(S_{\mathrm{sh,t}})$
3	$u(e_{\mathrm{L},f,\mathrm{A}})$	deviation from constant amplitude-frequency characteristic and linear phase-frequency characteristic of conditioning amplifier	$u_3(S_{\mathrm{sh,t}})$
4	$u(e_{\mathrm{L},f,\mathrm{T}})$	deviation from constant amplitude-frequency characteristic and linear phase-frequency characteristic of reference transducer	$u_4(S_{\mathrm{sh,t}})$
5	$u(e_{\mathrm{L},a,\mathrm{A}})$	amplitude (peak value) effect on amplifier gain	$u_5(S_{\mathrm{sh,t}})$
6	$u(e_{\mathrm{L},a,\mathrm{T}})$	amplitude (peak value) effect on sensitivity of transducer	$u_6(S_{\mathrm{sh,t}})$
7	$u(e_{\mathrm{I,A}})$	instability of reference amplifier gain, and effect of source impedance on gain and phase shift	$u_7(S_{\mathrm{sh,t}})$
8	$u(e_{\mathrm{I,T}})$	instability of transducer sensitivity (magnitude and phase shift)	$u_8(S_{\mathrm{sh,t}})$
9	$u(e_{\mathrm{E,A}})$	environmental effects on gain and phase shift of reference amplifier	$u_9(S_{\mathrm{sh,t}})$
10	$u(e_{\mathrm{E,T}})$	environmental effects on sensitivity (magnitude and phase shift) of reference transducer	$u_{10}(S_{\mathrm{sh,t}})$

Annex B
(informative)

Uncertainty examples — Expression of uncertainty of measurement in calibration

Tables B.1 to B.3 give examples of uncertainty calculations. All values in the tables are given after rounding.

Table B.1 — Anvil calibrator — Pneumatically operated piston shock calibrator[4]

Uncertainty component description		**Relative standard uncertainty** % (example value)	**Relative standard uncertainty** % (example value)
Amplitude range		(0,2 to 2) km/s^2	(2 to 100) km/s^2
Pulse duration range		(0,5 to 3,0) ms	(0,05 to 0,1) ms
A. Reference transducer			
1.	Reference sensitivity	0,5	0,5
2.	Relative motion	0,25	0,5
3.	Rotation/Transverse motion[a]	0,15	0,3
4.	Temperature	0,2	0,2
5.	Stability of reference sensitivity	0,1	0,1
6.	Amplitude linearity	0,05	0,25
B. Test transducer			
1.	Base strain/Mounting	0,2	0,2
2.	Rotation/Transverse motion	0,15	0,3
3.	Cable strain effects	0,1	0,2
4.	Temperature	0,5	0,5
5.	Frequency response[b]	0,0	0,0
C. Signal conditioning			
1.	Linearity of amplifiers and data acquisition	0,1	0,1
2.	Gain uncertainty	0,2	0,2
3.	Relative frequency response	0,1	0,5
4.	Temperature	0,1	0,1
D. Algorithm			
1.	Distortion on peak	0,2	0,5
2.	Zero baseline	0,2	0,2
3.	Noise on peak	0,05	0,05
Relative combined standard uncertainty		**0,9**	**1,7**
Relative expanded uncertainty U (k = 2)		**1,9**	**3,5**

[a] Additional masses on an anvil, asymmetric transducers, or cable forces can increase transverse motion significantly.

[b] Many piezoelectric transducers have a sloping frequency response. The frequency content of different pulse durations will result in a sensitivity that differs from a conventional 100 Hz vibration sensitivity. This is not considered an uncertainty.

Table B.2 — Uncertainty analysis for split-Hopkinson bar shock calibrator with velocity comparison[4]

	Uncertainty component description Amplitude range pulse duration range	Relative standard uncertainty % (example value) 100 km/s^2 0,3 ms
A. Reference velocity measurement (strain gauge)		
1.	Bar sensitivity	2,0
2.	Excitation voltage stability	0,2
3.	Attenuation, dispersion	0,5
4.	Temperature	0,5
5.	Stability of bar sensitivity	0,1
6.	Gauge factor non-linearity	0,1
7.	Cable, tape effects	0,2
B. Test transducer		
1,	Base strain/Mounting	0,5
2.	Rotation/Transverse motion	0,5
3.	Cable strain effects	0,2
4.	Temperature	0,5
5.	Frequency response[a]	0,5
C. Signal conditioning		
1.	Linearity of amplifiers and data acquisition	0,1
2.	Gain uncertainty	0,2
3.	Relative frequency response	0,5
4.	Temperature	0,1
D. Algorithm		
1.	Test transducer zero, integration frequency response	1,0
2.	Test transducer nonlinearity	0,5
3.	Bar zero baseline	0,2
4.	Noise on bar peak	0,05
Relative combined standard uncertainty		**2,7**
Relative expanded uncertainty U (k = 2)		**5,4**

[a] Many piezoelectric transducers have a sloping frequency response. The frequency content of different pulse durations will result in a sensitivity that differs from a conventional 100 Hz vibration sensitivity. This is not considered an uncertainty.

NOTE The procedure for determining uncertainties is described in ISO 16063-1:1998, Annex A.

Table B.3 — Uncertainty analysis for split-Hopkinson bar shock calibrator with comparison to a force transducer[13]

Uncertainty component description	**Relative standard uncertainty** % (example value)
A. Reference quartz transducer	
1. d_{11} for x-cut quartz (variability, orientation, temperature)	2,7
2. Quartz alignment and coupling	—
3. Quartz output variability (release waves, ε vs strain, etc.)	1,0
4. Fly-away mass, M	0,3
5. Preamplifier/amplifier (calibration for conditions of use; linearity with V and frequency; stability between calibrations)	0,7
6. Recorder (resolution, frequency response, stability)	0,3
7. Peak-reading algorithm (procedure, noise) 0,1	0,1
B. Transducer under test	
1. Mounting	—
2. Signal conditioner/amplifier (calibration for conditions of use; linearity with voltage and frequency; stability between calibrations)	
3. Recorder (resolution, frequency response, stability)	0,3
4. Transverse response and resonances	—
5. Peak-reading algorithm (procedure, noise)	0,1
6. Loss of energy response beyond cut-off not matched by similar loss from the quartz reference	~3
7. Random variation in S	2,5
Relative combined standard uncertainty	**5,0**
Relative expanded uncertainty U (k = 2)	**10,0**
NOTE The procedure for determining uncertainties is described in ISO 16063-1:1998, Annex A.	

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