Guidelines on the Calibration of Electromechanical and Mechanical Manometers

EURAMET Calibration Guide No. 17
Version 3.0 (04/2017)

Mass and Related Quantities

Version 3.0 (04/2017)

Guidelines on the Calibration of Electromechanical and Mechanical Manometers

Purpose

This document has been produced to enhance the equivalence and mutual recognition of calibration results obtained by laboratories performing calibrations of electromechanical and mechanical manometers.

Authorship and imprint

This document was developed by the EURAMET e.V., Technical Committee for Mass and Related Quantities.
Authors: Wladimir Sabuga (PTB, Germany), Oliver Ott (PTB, Germany), Yasin Durgut (UME, Turkey), Janez Šetina (IMT, Slovenia), Pierre Otal (LNE, France), Nieves Medina (CEM, Spain), Aykurt Altintas (FORCE Technology, Denmark).

Version 3.0 April 2017
Version 2.0 March 2011
Verson 1.0 July 2007

EURAMET e.V.
Bundesallee 100
38116 Braunschweig
Germany

E-mail: secretariat@euramet.org
Phone: +49 531 592 1960

Official language

The English language version of this document is the definitive version. The EURAMET Secretariat can give permission to translate this text into other languages, subject to certain conditions available on application. In case of any inconsistency between the terms of the translation and the terms of this document, this document shall prevail.

Copyright

ISBN 978-3-942992-48-0

Image on cover page by PTB.

Guidance publications

This document gives guidance on measurement practices in the specified fields of measurements. By applying the recommendations presented in this document, laboratories can produce calibration results that can be recognised and accepted throughout Europe. The approaches taken are not mandatory and are for the guidance of calibration laboratories. The document has been produced as a means of promoting a consistent approach to good measurement practice leading to and supporting laboratory accreditation.

The guide may be used by third parties, e.g. National Accreditation Bodies, peer reviewers, witnesses to measurements, etc., as a reference only. Should the guide be adopted as part of a requirement of any such party, this shall be for that application only and the EURAMET Secretariat should be informed of any such adoption.

On request EURAMET may involve third parties in stakeholder consultations when a review of the guide is planned. If you are interested, please contact the EURAMET Secretariat.

No representation is made nor warranty given that this document or the information contained in it will be suitable for any particular purpose. In no event shall EURAMET, the authors or anyone else involved in the creation of the document be liable for any damages whatsoever arising out of the use of the information contained herein. The parties using the guide shall indemnify EURAMET accordingly.

Further information

For further information about this document, please contact your national contact person in the EURAMET Technical Committee for Mass and Related Quantities (see www.euramet.org).

Content

1 INTRODUCTION

This document deals with the calibration of electromechanical and mechanical manometers.

The Guidelines provide the users of electromechanical and mechanical manometers with the fundamentals necessary for establishing and applying calibration procedures.

These Guidelines apply to all electromechanical manometers for measuring absolute, positive and negative gauge and differential pressures, as well as to bourdon tube manometers.

Notes: The Guidelines refer to the "measurement" function of a measuring pressure controller in particular.

The Guidelines do not refer to piezoelectric pressure transducers.

2 REFERENCE DOCUMENTS AND LITERATURE

DIN EN 472, Pressure gauges – Vocabulary, 1994

DIN EN 837-1, Pressure gauges – Part 1: Bourdon tube pressure gauges – Dimensions, metrology, requirements and testing, 1997

DIN EN 837-2, Pressure gauges – Part 2: Selection and installation recommendations for pressure gauges, 1997

DIN EN 837-3, Pressure gauges – Part 3: Diaphragm and capsule pressure gauges – Dimensions, metrology, requirements and testing, 1997

DIN EN 12645, Tyre pressure measuring instruments – Devices for inspection of pressure and/or inflation/deflation of tyres for motor vehicles – Metrology, requirements and testing, 2015

DIN EN 61298-2, Process measurement and control devices – General methods and procedures for evaluating performance – Part 2: Tests under reference conditions, 2009

EA-4/02 M (rev 01), Evaluation of the uncertainty of measurement in calibration, 2013

EURAMET cg-3 (Version 1.0), Calibration of pressure balances, 2011

IEC 60770, Transmitters for use in industrial-process control; Part 1: Methods for performance evaluation, 2010; Part 2: Methods for inspection and routine testing, 2010

ILAC P10:01/2013 ILAC policy on the traceability of measurement results, 2013

JCGM 100, GUM 1995 with minor corrections, Evaluation of measurement data - Guide to the expression of uncertainty in measurements, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, 2008 (revised in 2010)

JCGM 200 (3rd edition), International vocabulary of metrology - Basic and general concepts and associated terms (VIM), issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, 2012

RM Aero 802 41, Calibration and check of electromechanical manometers, Bureau de Normalisation de l'Aéronautique et de l'Espace, BNAE, 1993 (in French)

3 DEFINITIONS

In order to avoid ambiguity, the terms mentioned below have the following meanings:

Line pressure: Static pressure used as a reference for differential pressures.

Reference level: Level at which the value of the applied pressure is quantified.

Note: The manufacturer of the instrument specifies this level. If this is not the case, the calibration laboratory shall specify it.

4 PRINCIPLES OF THE ELECTROMECHANICAL AND MECHANICAL MANOMETERS

The Guidelines deal with three types of electromechanical manometers:

- pressure transducers,
- pressure transmitters,
- manometers with digital or analogue indication

and with mechanical bourdon tube manometers.

4.1 Pressure transducers

Pressure transducers convert the measured pressure into an analogue electrical signal that is proportional to the applied pressure.

According to the model, the output signal can be:

- a voltage,
- a current,
- a frequency.

To ensure that they function, the pressure transducers need a continuous power supply stabilised to a level in relation to the expected uncertainty of the pressure measurement.

4.2 Pressure transmitters

A pressure transmitter is generally a unit that consists of a pressure transducer and a module for conditioning and amplifying the transducer signal.

Depending on the model, the output information of a pressure transmitter may be:

- a voltage (5 V; 10 V; ...),
- a current (4 mA – 20 mA; ...),
- a relative resistance change (1 mV/V; ...),
- a frequency, or
- a digital format (RS 232; ...).

For operation, pressure transmitters need a continuous electrical supply, which need not be specifically stabilised.

4.3 Manometers with digital or analogue indication

This type of manometer is a complete measuring instrument that indicates units of pressure. According to the pattern, it may consist of the following units:

(a) Manometer with a digital indication:

- pressure transducer,
- analogue conditioning module,
- analogue-to-digital converter,
- digital processing module,

- digital indication (in the unit(s) specified by the manufacturer),
- electrical power supply unit (generally incorporated).

(b) Manometer with an analogue indication:

- pressure transducer,
- analogue conditioning module,
- analogue indicating module,
- electrical power supply unit (generally incorporated).

These elements may be accommodated in one housing (internal transducer) or constitute separate devices, one of which is the transducer (external transducer).

The manometers may also be equipped with analogue or digital output ports.

Note: Calibration of such an instrument should be performed for each output of interest.

4.4 Bourdon tube manometers

This type of manometer is a complete measuring instrument that indicates units of pressure. It consists of the following units:

- pressure-responsive element (Bourdon tube),
- movement,
- pointer,
- dial.

These parts shall be installed inside an enclosing case.

5 LABORATORY CALIBRATION PROCEDURES

5.1 Installation of the equipment

The following instructions should be followed when installing the equipment:

- Protect the equipment from direct sunlight.
- Place the instrument to be calibrated as close as possible to the reference standard.
- Ensure that the pressure reference levels of both instruments are as close as possible and account for the difference in the pressure reference level when calculating corrections and uncertainties.
- The equipment should be switched on in the calibration environment before starting the calibration in order to reach thermal equilibrium in the whole system.
- Take into account the manufacturer's specification for mounting position, torque, warm-up, for example.

The calibration is to be carried out after temperature equalization between calibration item and environment. A period for warming up the calibration item or potential warming-up of the calibration item due to the supply voltage is to be taken into account. The calibration is to be performed at an ambient temperature stable to within ±1 °C; this temperature must lie between 18 °C and 28 °C and is to be recorded. If the air density has an effect on the calibration result, not only the ambient temperature but also the atmospheric pressure and the relative humidity are to be recorded.

5.2 Methods of calibration

If appropriate, the procedure of calibration should allow – according to the client's requirements – the evaluation of the hysteresis, the linearity and the repeatability of the instrument to be calibrated.

The applied procedure depends on the target uncertainty of the instrument according to the client's requirements and can limit the lowest achievable uncertainty.

Generally, the calibration is to be carried out in pressure points uniformly distributed over the calibration range. In the Sections 5.2.1, 5.2.2 and 5.2.3, there are exemplary recommendations for a calibration range from 0 % FS (full scale) to 100 % FS including the zero point as one point to illustrate the procedures.

The comparison between the measurement values of the instrument to be calibrated and the reference standard can be performed by two different methods:

- adjustment of the pressure according to the indication of the instrument to be calibrated,
- adjustment of the pressure according to the indication of the reference standard.

5.2.1 Basic Calibration Procedure

The Basic Calibration Procedure should be used for instruments where the expanded measurement target uncertainty (k = 2) is $U \geq 0.2$ % FS. Calibration is performed in one measuring cycle at six pressure points consisting of a series of increasing pressure and a series of decreasing pressure.

Repeatability is estimated from calibration in a measuring series of increasing pressure at two pressure points (preferably 0 % FS and another one around the centre of the calibrated pressure range, e.g. 40 % FS or 60 % FS) that is measured three times. The repeatability value is then applied to all other pressure points.

Using the Basic Calibration Procedure the expanded measurement uncertainty (k = 2) of the calibrated instrument may not be reported smaller than 0.2 % FS.

5.2.2 Standard Calibration Procedure

The Standard Calibration Procedure should be used for instruments where the expanded measurement target uncertainty (k = 2) is 0.05 % FS $\leq U <$ 0.2 % FS. Calibration is performed in one measuring cycle at 11 pressure points consisting of a series of increasing pressure and a series of decreasing pressure.

Repeatability is estimated from calibration in a measuring series of increasing pressure at four pressure points (preferably 0 % FS, 20 % FS, 50 % FS and 80 % FS) that is measured three times. At the remaining pressure points, the biggest of the repeatability values as measured in the neighbouring points is taken. This means that at 10 % FS, the repeatability at 0 % FS or at 20 % FS is taken, whichever is bigger. At 30 % FS and 40 % FS, the repeatability at 20 % FS or at 50 % FS is taken, whichever is bigger. At 60 % FS and 70 % FS, the repeatability at 50 % FS or at 80 % FS is taken, whichever is bigger. At 90 % FS and 100 % FS, the repeatability at 80 % FS is taken.

Using the Standard Calibration Procedure the expanded measurement uncertainty (k = 2) of the calibrated instrument may not be reported smaller than 0.05 % FS.

5.2.3 Comprehensive Calibration Procedure

The Comprehensive Calibration Procedure should be used for instruments where the expanded measurement target uncertainty (k = 2) is U < 0.05 % FS. Calibration is performed at 11 pressure points in three measuring cycles, each consisting of a series of increasing pressure and a series of decreasing pressure.

5.3 Equipment set-up

5.3.1 Reference instrument

The reference instrument shall comply with the following requirements:

- It shall be traceable to national or international standards.
- Its uncertainty shall be better (if practicable) than that of the instrument to be calibrated, the ratio being in general equal to or greater than 2.

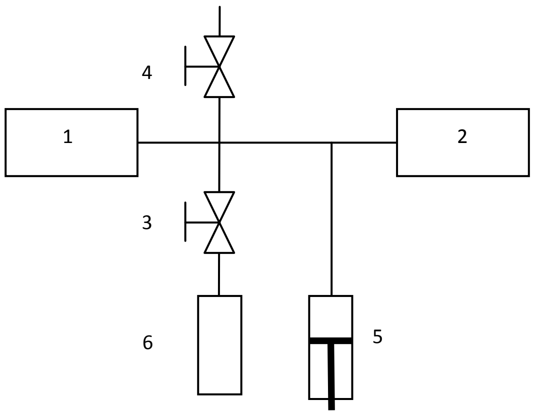
5.3.2 Mechanical set-up

For calibrations in gaseous media it is strongly recommended to use a pressurised container with dry and clean gas as the pressure source. The container must be equipped with a pressure-reducing valve or connected to a pressure control valve if required by the measurement range of the instrument to be calibrated.

In order to ensure the quality of the gas, the vacuum pump – if required – shall be equipped with accessories such as traps and isolating valves.

5.3.2.1 Positive gauge pressure in gaseous media

The typical set-up may be as follows (see Figure 1):



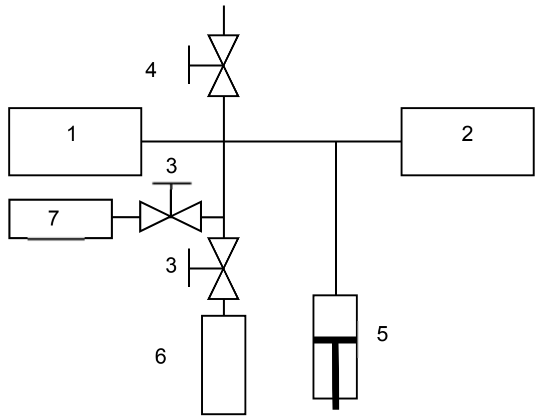
1 reference standard
2 instrument to be calibrated, mounted as normally used
3 fine-regulated inlet valve
4 fine-regulated pressure relief valve
5 volume regulator
6 pressure source

Figure 1 – Set-up in positive gauge pressure, gaseous media

The required pressure is roughly established using inlet or outlet valves depending on whether the pressure is supposed to be set up from low pressure or from high pressure. The final pressure adjustment is performed using a volume regulator.

5.3.2.2 Absolute and negative gauge pressure in gaseous media

The typical set-up may be as follows (see Figure 2):



1 reference standard
2 instrument to be calibrated, mounted as normally used
3 fine-regulated inlet valves
4 fine-regulated pressure relief valve
5 volume regulator
6 pressure source
7 vacuum pump (for pressures below atmospheric pressure)

Figure 2 – Set-up in absolute and negative gauge pressure, gaseous media

The required pressure is roughly established using inlet or outlet valves depending on whether the pressure is supposed to be set up from low pressure or from high pressure. The final pressure adjustment is performed using a volume regulator.

In the case of absolute pressures significantly higher than the atmospheric pressure, the use of a gauge pressure reference standard and a barometric pressure-measuring reference standard is acceptable. The set-up recommended for positive gauge pressures is applicable. The value of the absolute pressure is obtained by the summation of the values of the pressures measured with the two reference standards.

5.3.2.3 Differential pressure in gaseous media

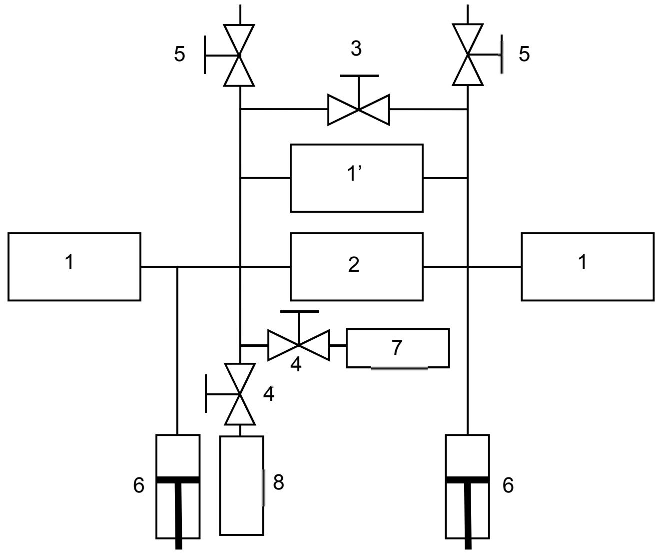
The set-up depicted in Figure 3 is recommended.

The required line pressure is roughly established using inlet or outlet valves depending on whether the pressure is supposed to be set up from low pressure or from high pressure. The final pressure adjustment is performed using a volume regulator. During this procedure the bypass valve is open.

The required differential pressure is set up using one of the volume regulators.

Instead of using two reference standards, a differential pressure standard or a twin pressure balance may be used.

A vacuum pump arranged downstream of the inlet valve allows the line pressure to be lower than the atmospheric pressure.



1 two reference standards (or a differential pressure standard 1')
2 instrument to be calibrated, mounted as normally used
3 bypass valve
4 fine-regulated inlet valves
5 fine-regulated pressure relief valves
6 two volume regulators
7 vacuum pump (for line pressures below atmospheric pressure)
8 pressure source

Figure 3 – Set-up in differential pressure, gaseous media

5.3.2.4 Hydraulic pressure

The set-up for hydraulic gauge pressure and hydraulic differential pressure is basically the same as that for gaseous media (cf. Sections 5.3.2.1 and 5.3.2.3) with the following options:

- the relief valves are replaced with discharge valves connected to a reservoir of pressure transmitting fluid,
- the pressure sources are replaced by screw press and/or priming pump,
- the vacuum pump (cf. Figure 3) is not required.

For absolute liquid pressures, refer additionally to the last paragraph of Section 5.3.2.2.

5.3.3 Electrical set-up

This section refers only to transducers and transmitters with an analogue output signal.

If the transducer being calibrated is equipped with a signal conditioner, then follow the manufacturer's instructions concerning the electrical set-up.

If no signal conditioner is available, a relevant data sheet with the manufacturer's specifications should be available.

If applicable, the voltmeter and the reference standard resistor shall be calibrated and traceable to the corresponding national/international standard.

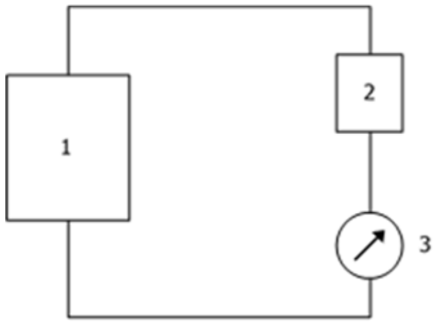
In every case, it is important to follow the recommendations concerning the electrical shielding, to ensure the quality of the connections (of the "low-level" transducers in particular), to meet the safety requirements. Some instruments may be supplied with a power supply system or are supposed to be connected to such a system.

According to the instrument type, various set-ups are possible. This guide deals only with the three most typical set-ups which are presented below.

5.3.3.1 Two-wire transmitters

Generally, this is the case of instruments with DC loop (4 – 20) mA. However, some other output signals (0 to 10 mA, 0 to 20 mA or 0 to 50 mA) are applicable.

The typical set-up may be as follows (see Figure 4):



1 transmitter
2 power supply
3 measurement (reading unit)

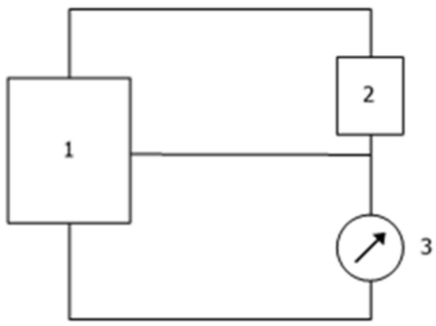
Figure 4 – Electrical set-up, two-wire transmitters

The current I can be determined by measuring the voltage V at the terminals of a calibrated standard resistor R in the circuit via $I = V/R$.

It is recommended to follow the manufacturer's instructions concerning the values of the power supply voltage and the resistor or the client's specifications when appropriate.

5.3.3.2 Three-wire transmiters or transducers

These are generally instruments with a Wheatstone bridge. The typical set-up may be as follows (see Figure 5):



1 transmitter or transducer
2 power supply
3 measurement (reading unit)

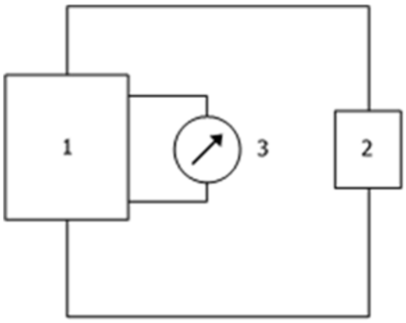
Figure 5 – Electrical set-up, three-wire transmitters or transducers

For the selection of the power supply and the voltage-measuring instrument, it is recommended to follow the manufacturer's specifications. The resistor of this instrument shall, however, be sufficiently high (at least 10 times) compared with the internal resistance of the transmitter or transducer.

5.3.3.3 Four-wire transmitters or transducers

These are generally instruments with a Wheatstone bridge.

The typical set-up is as follows (see Figure 6):



1 transmitter or transducer
2 power supply
3 measurement (reading unit)

Figure 6 – Electrical set-up, four-wire transmitters or transducers

As the output signal is a low-level signal, it is important to ensure the appropriate quality of the earth connections and of the shielding.

Variants:

- The output signal is an amplified signal from the amplifier (high-level outputs) incorporated in the transmitter.
- Some instruments may include a probe for temperature compensation; the output of this probe may consist of one or two supplementary wires.

5.4 Calibration sequences

5.4.1 Preparatory work

Prior to the calibration itself, the calibratability of the instrument to be calibrated is a necessary presupposition. The good working condition of the instrument shall be visually confirmed, especially regarding:

- the inscriptions,
- the instrument being undamaged, the cleanliness of the instrument (free of contamination),
- the good quality of the electrical contacts,
- the readability of indications, the setting elements adjusted in defined positions
- the documents necessary for calibration (technical data, operating instructions).

It is recommended to perform the following operations:

- identify the reference levels
  - of the reference,
  - of the instrument to be calibrated (at the level of the connection or at the reference level defined by the manufacturer),
- minimise the difference between the reference levels,
- for torque sensitive devices, follow the manufacturer's instructions,
- make sure that there is no leakage by checking the set-up at the upper pressure limit, the pressure must be stable.

5.4.2 Calibration procedures

In the case of instruments with several outputs, it is sufficient to perform the calibration for the output(s) specified by the user.

Irrespective of the instrument to be calibrated and of the procedure to be used (refer to Section 5.2), the operations are performed in three successive steps:

- check of a limited number of pressure points of the measurement range to determine the initial metrological condition of the instrument,
- adjustment of the instrument according to the manufacturer's specification,
- calibration appropriate to the instrument over its whole measurement range or span.

Each of these operations, especially the adjustment of the instrument, shall be performed only with the agreement of the client and shall be reported in the calibration certificate.

The general proceeding for calibration measurements is as follows:

- Prior to the calibration procedure itself, bring the instrument at least twice to its upper pressure limit and keep the pressure for at least one minute; the time between the preloadings should be at least one minute. The preloadings should be repeated after a change of the mounting for the determination of the reproducibility.
- After preloading and after reaching steady-state conditions the instrument is set to zero, if possible. The zero reading is carried out immediately afterwards.
- For the variation of the pressure points in a measurement series, the time between two successive pressure points should be the same and should not be shorter than 30 seconds. The reading should be made 30 seconds after the end of the pressure change at the earliest.
- The measurement value for the upper limit of the calibration range is to be recorded prior to and after the waiting time of at least two minutes (five minutes for bourdon tube manometers).
- The zero reading at the end of a measuring cycle is made 30 seconds after complete relief at the earliest.
- The adjustment of the pressure during the repeated measuring series should be as close as possible to the values of the individual pressures of the first measuring series. The difference between the reference pressures in the repeated measuring series must not be bigger than 1 % of the calibration range.

Note: The reading of a bourdon tube manometer shall be obtained after the gauge has been lightly tapped in order to minimise the error caused by the friction of movement components.

5.4.2.1 Initial check

To determine the long-term drift of the instrument, it is necessary to provide the user with some information on its condition prior to any potential adjustment.

If the user does not apply for a complete calibration to be carried out prior to the adjustment, it is recommended to perform the following operations:

- operate the instrument and preload it as described above,
- during the first pressure rise, check the indication obtained for conformity with the specifications,
- read the indications of the instrument at 0 %, 50 % and 100 % of its measurement span.

5.4.2.2 Adjustment

If the response of the instrument does not conform to the conventional response during the initial check in any of the check points (5.4.2.1), e.g.:

- for a digital manometer with direct reading, if there is a difference between the indicated pressure and the applied pressure,
- for a transmitter with electrical output, if there is a deviation from the conventional signal of, for example, 4 mA to 20 mA,
- for a bourdon tube manometer with direct reading, if there is a difference between the indicated pressure and the applied pressure based on manometer accuracy class,

then perform an adjustment of the instrument according to the client's requirements.

Depending on the capabilities of the calibration laboratory such a procedure shall be performed:

- with the aid of the means normally accessible to the user (potentiometers for zero and full scale, sometimes with mid-scale),
- with the internal adjustment facilities of the instrument (potentiometers, storage of a calibration curve, etc.), in conformity with the information contained in the technical description, after agreement of the client.

Note: This operation obviously presumes a detailed knowledge of the adjustment procedures and requires specialised operators and calibration means that are more powerful than the instrument to be calibrated.

If the instrument provides scale marks which are useful to the user (calibration notches, restitution of a calibration curve for example), it is recommended to determine these elements in order to report them in the calibration certificate.

5.4.2.3 Main calibration

The calibration procedure to be used (cf. Section 5.2) is selected according to the target uncertainty of measurement for the instrument to be calibrated.

At each calibration point at least the following data shall be recorded:

- the pressure indicated by the reference instrument or the elements necessary for calculating the pressure actually measured (values of masses and temperature for a pressure balance, for example),

- the indication of the instrument to be calibrated.

The following data shall also be recorded:

- the identification parameters of the reference instrument,
- the values of the influence quantities such as temperature, atmospheric pressure and relative humidity,
- the identification parameters of the instrument to be calibrated,
- the identification of the instruments included in the measuring system and/or the instrument used for measuring the output signal.

5.4.3 Presentation of results

In general, it is recommended to present the results of a calibration in a form that can be easily evaluated by the users of the measuring instrument under calibration. It is essential to present clearly the results of the calibration and the methods of modelling or interpolation (if applicable).

In order to take into account a specific method of measurement uncertainty evaluation and calculation, the results are presented differently depending on whether the measuring instrument under calibration provides:

- an output signal in an electric unit (pressure transducers and transmitters),
- an indication in a pressure unit (manometers with digital or analogue indication).

Table 1

	Calibration results				**Model**		
	Applied pressure p_{ref}	Applied pressure p_{ref}	Mean of output signal	Standard deviation of output signal	Modelled indicated pressure $p_{ind,mod}$	Deviation $p_{ind,mod} - p_{ref}$	Expanded uncertainty of deviation
	1)	2)	3)	3), 4)	5)	5)	5), 6)
Increasing pressure							
Decreasing pressure							

1) The pressure measured by the reference instrument at the reference level of the instrument to be calibrated, expressed in pascals or multiples. Instead of this column, the conversion coefficient of the instrument pressure unit to the pascal can be given.

2) The pressure measured by the reference instrument at the reference level of the instrument to be calibrated, expressed in the unit of the output signal of the instrument to be calibrated.

3) Value expressed in the unit of the output signal of the instrument to be calibrated.

4) Calculated at every measurement point if at least three values are available.

5) Value expressed in the pressure unit of the instrument to be calibrated. Reporting the model in the calibration certificate is optional.

6) The uncertainty determined according to Section 6.

Table 2

	Applied pressure p_{ref}	Applied pressure p_{ref}	Indicated pressure p_{ind}	Standard deviation of Measurement	Deviation $p_{ind} - p_{ref}$	Expanded uncertainty of deviation
	1)	2)	3)	3)	3)	3), 4)
Increasing pressures						
Decreasing pressures						

1) The pressure measured by the reference instrument at the reference level of the instrument to be calibrated, expressed in pascals or multiples. Instead of this column, the conversion coefficient of the instrument pressure unit to the pascal can be given.

2) Pressure measured by the reference instrument at the reference level of the instrument to be calibrated, expressed in the pressure unit of the instrument to be calibrated.

3) Value expressed in the pressure unit of the instrument to be calibrated.

4) Evaluated according to Section 6.

5.4.3.1 Case of pressure transducers and transmitters

Whatever the modelling is, calibration results may be presented in the form of Table 1.

It should be noted that the standard deviation of the input signal (generally very small) is not presented in this table because the deviation is taken into account in the uncertainty of the measurements performed with the reference instrument.

5.4.3.2 Case of manometers with digital or analogue indication

Calibration results may be presented in the form of Table 2.

6 DETERMINATION OF THE UNCERTAINTY OF MEASUREMENT

6.1 Common aspects of determining the uncertainty of measurement

The principal elements to be taken into account for the evaluation of the uncertainty of the calibration result for an electromechanical or mechanical manometer are,

for a pressure transducer or transmitter:

- uncertainty of the reference instrument in the conditions of use (cf. calibration certificate, long-term stability, environmental conditions, for example),
- uncertainty due to zero error,
- uncertainty due to repeatability,
- uncertainty due to reproducibility of the instrument under calibration where applicable,
- uncertainty due to reversibility (hysteresis) of the instrument under calibration,
- uncertainty of the measuring instruments used during the calibration (voltage, current, frequency, etc.) including their resolution,
- uncertainty due to influence quantities,
- uncertainty due to power supply for the low-level transducers (in the case where

the output signal is proportional to the supply voltage the uncertainty of measurement and the short-term stability of the supply voltage have to be taken into account),

- uncertainty due to modelling (standard deviation of measurement results from the model equation),
- uncertainty due to estimation of the head correction between the instrument to be calibrated and the reference instrument;

for a manometer with digital or analogue indication:

- uncertainty of the reference instrument in the conditions of use (cf. calibration certificate, long-term stability, environmental conditions, for example),
- uncertainty due to zero error,
- uncertainty due to repeatability,
- uncertainty due to reproducibility of the instrument under calibration where applicable,
- uncertainty due to the resolution of the instrument to be calibrated,
- uncertainty due to reversibility (hysteresis) of the instrument under calibration,
- uncertainty due to estimation of the head correction between the instrument to be calibrated and the reference instrument.

Procedure

The uncertainty of the calibration results shall be evaluated following the principles published in the EA document 4/02 and JCGM 100.

When analysing the uncertainty budget, the terms and rules of calculation stated in Table 3 are used assuming that no correlation between the input quantities must be taken into consideration.

Relative uncertainties are stated by the variables *w*, *W* to distinguish them from the absolute uncertainties *u*, *U*.

In addition to this general rule of calculating uncertainties, there are two special cases which lead to a simple quadratic addition of either the absolute uncertainties *u*, *U* or the relative uncertainties *w*, *W*. In the case of the sum/difference model, the sensitivity coefficients take the value $c_i = \pm 1$; in the case of the product/quotient model the sensitivity coefficients result in $c_i = \pm y \cdot x^{-1}$.

Table 3

Model function			$y = f(x_1, x_2, \ldots x_N)$
Standard uncertainty of measurement	$u(x_i)$	the standard uncertainty associated with the input quantity x_i	
	c_i	sensitivity coefficient	$c_i \equiv \frac{\partial f}{\partial x_i}$
	$u_i(y)$	contribution to the standard uncertainty associated with the result, caused by the standard uncertainty $u(x_i)$ of the input quantity x_i	$u_i(y) \equiv \lvert c_i \rvert \cdot u(x_i)$
	$u(y)$	standard uncertainty associated with the result	$u^2(y) = \sum_{i=1}^{N} u_i^2(y)$ $u(y) = \sqrt{\sum_{i=1}^{N} u_i^2(y)}$
Expanded uncertainty of measurement	$U(y)$	expanded uncertainty of measurement	$U(y) = k \cdot u(y)$
	k	coverage factor	$k = 2$ [1]

Sum/difference model

$$Y = X + \sum_{i=1}^{N} \delta X_i \tag{1}$$

Y	output quantity
X	input quantity/quantities on which the measurand depends
δX_i	unknown uncorrected error(s)
$E[\delta X_i] = 0$	expected values (no contributions to the output quantity but to the uncertainty of measurement)

This model is suited to determine, for example, the deviations of indicating pressure gauges (cf. Section 6.2 for the meaning of the indices):

$$\Delta p = p_{\text{ind}} - p_{\text{ref}} + \sum_{i=1}^{N} \delta p_i \tag{2}$$

[1] The expanded uncertainty of measurement $U(y)$ shall encompass the shortest possible interval with a coverage probability of approximately 95 %. The coverage factor k is implicitly defined by $U(y) = k \cdot u(y)$. If, as is usually the case in practice, the probability distribution associated with the measurand is normal (Gaussian), then $U(y)$ shall be taken as $2 \cdot u(y)$, i.e. k = 2.

Product/quotient model

$$Y = X \cdot \prod_{i=1}^{N} K_i \qquad (3)$$

Y	output quantity
X	input quantity/quantities on which the measurand depends
$K_i = \left(1 + \delta X_i / X_j\right)$	correction factor(s)
δX_i	unknown uncorrected error(s)
X_j	quantity/quantities to which δX_i is related
$E[\delta X_i] = 0$; $E[K_i] = 1$	expected values (no contributions to the output quantity but to the uncertainty of measurement)

This model is suited to determine, for example, the transmission coefficient S of a pressure transducer with electrical output using preferably relative uncertainties of measurement for the uncertainty analysis:

$$S = \frac{X_{\text{output}}}{X_{\text{input}}} = \frac{V_{\text{ind}} \;/(G \cdot V_{\text{PS}})}{p_{\text{ref}}} \cdot \prod_{i=1}^{N} K_i \qquad (4)$$

Input quantities

The uncertainties of measurement associated with the input quantities are grouped into two categories according to the way in which they have been determined:

Type **A**: The value and the associated standard uncertainty are determined by methods of statistical analysis for measurement series carried out under repeatability conditions.

Type **B**: The value and the associated standard uncertainty are determined on the basis of other information, for example:

- previous measurement data (for example, from type approvals),
- general knowledge of and experience with the properties and the behaviour of measuring instruments and materials,
- manufacturer's specifications,
- calibration certificates or other certificates,
- reference data taken from handbooks.

In many cases, only the upper and lower limits a_+ and a_- can be stated for the value x_i of a quantity, and a probability distribution with constant probability density between these limits can be assumed. This situation is described by a rectangular probability distribution.

With

$$a_+ - a_- = 2a \qquad (5)$$

the estimate of the input quantity

$$x_i = \frac{1}{2}\left(a_+ + a_-\right) \qquad (6)$$

and the attributed standard uncertainty

$$u(x_i) = \frac{a}{\sqrt{3}} \tag{7}$$

are obtained.

6.2 Guidance on uncertainty calculation for selected practical cases

6.2.1 Calibration of a digital or analogue manometer

Choice of the model

The sum/difference model is used to determine the indication deviation and its uncertainty separately for values measured at increasing (index up) and decreasing (index dn, for down) pressure:

$$\Delta p_{\text{up/dn}} = p_{\text{ind,up/dn}} - p_{\text{ref,up/dn}} + \sum_{i=1}^{2} \delta p_i = p_{\text{ind,up/dn}} - p_{\text{ref,up/dn}} + \delta p_{\text{zero}} + \delta p_{\text{repeat,up/dn}} \tag{8}$$

The symbols are explained in Table 4.

Table 4

$Y = \Delta p_{\text{up/dn/mean}}$	measurand; deviation of the indication
$X_1 = p_{\text{ind,up/dn/mean}}$	indication of the pressure gauge
$X_2 = p_{\text{ref,up/dn/mean}}$	pressure generated by reference standard[2]
$\delta X_1 = \delta p_{\text{zero}}$	unknown uncorrected measurement error due to zero error
$\delta X_2 = \delta p_{\text{repeat,up/dn/mean}}$	unknown uncorrected measurement error due to repeatability

The limited resolution of the indication (in Table 5 given by the variability interval $2a = r$ for a device with digital indication) has to be taken into account as part of the uncertainty analysis.

The mean values of the indication and the reference pressure are obtained by:

$$p_{\text{ind,mean}} = \frac{p_{\text{ind,up}} + p_{\text{ind,dn}}}{2}\ ,\ p_{\text{ref,mean}} = \frac{p_{\text{ref,up}} + p_{\text{ref,dn}}}{2} \tag{9}$$

To calculate the deviation Δp_{mean} of the mean indication, the contribution of the hysteresis effect has to be taken into account:

$\delta X_3 = \delta p_{\text{hysteresis}}$	unknown uncorrected measurement error due to hysteresis

$$\begin{aligned}\Delta p_{\text{mean}} &= p_{\text{ind,mean}} - p_{\text{ref,mean}} + \sum_{i=1}^{3} \delta p_i \\ &= p_{\text{ind,mean}} - p_{\text{ref,mean}} + \delta p_{\text{zero}} + \delta p_{\text{repeat,mean}} + \delta p_{\text{hysteresis}}\end{aligned} \tag{10}$$

In addition, a contribution of the reproducibility after reinstallation has to be taken into

[2] The pressure generated by the reference standard in the reference level of the calibration object must be corrected for the influence of the conditions of use. In consequence, the uncertainty analysis also covers uncertainty components which take the difference between reference and calibration conditions into account.

account where applicable:

$\delta X_4 = \delta p_{\text{reprod,up/dn/mean}}$	unknown uncorrected measurement error due to reproducibility

Uncertainty calculation

When the series at increasing and decreasing pressures are analysed separately, the expanded uncertainty of measurement (k = 2) becomes

$$U(\Delta p_{\text{up/dn}}) = k\sqrt{u_{\text{ref}}^2 + u_{\text{ind,up/dn}}^2 + u_{\text{zero}}^2 + u_{\text{repeat,up/dn}}^2} \quad (11)$$

For the usage of symbols refer also to Table 5.

In the applications of the calibration object it is often useful to combine the expanded uncertainty U with the deviation Δp. This provides information about the maximum deviation of one single measurement result from the correct value (as issued from the value that would have been measured with the standard instrument).

For this purpose, a so-called error span[3] U' can be defined:

$$U'(\Delta p_{\text{up/dn}}) = U(\Delta p_{\text{up/dn}}) + |\Delta p_{\text{up/dn}}| \quad (12)$$

To calculate the uncertainty of the mean values of the increasing and decreasing pressure series, the contribution of the hysteresis effect must be included:

$$U(\Delta p_{\text{mean}}) = k\sqrt{u_{\text{ref}}^2 + u_{\text{ind,mean}}^2 + u_{\text{zero}}^2 + u_{\text{repeat,mean}}^2 + u_{\text{hysteresis}}^2} \quad (13)$$

The largest uncertainty of the repeatabilities $u_{\text{repeat,up/dn}}$ at each calibration pressure is used as the value $u_{\text{repeat,mean}}$. The error span $U'(\Delta p_{\text{mean}})$ is obtained accordingly:

$$U'(\Delta p_{\text{mean}}) = U(\Delta p_{\text{mean}}) + |\Delta p_{\text{mean}}| \quad (14)$$

Information available about the input quantities

The knowledge about the input quantities can be summarised in a table (Table 5 exemplifies a device with digital indication).

Statement of a single value

In addition to the error span for each calibration pressure, the maximum error span in the range covered by the calibration (in pressure units or related to the measured value or the measurement span) may be stated. Compliance with specified maximum permissible errors can also be confirmed (statement of compliance).

[3] The error span is the maximum difference to be expected between the measured value and the conventional true value of the measurand. The error span can be used in technical specifications to characterise the accuracy of the calibrated instrument.

Table 5

No.	Quantity	Estimate	Unit[4]	Variability interval	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty
	X_i	x_i		$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$
1	$p_{\text{ind,up/dn/mean}}$	$p_{\text{ind,up/dn/mean},j}$	Pa	r (resolution)	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{r}{2}\right)^2}$	1	$u_{\text{ind,up/dn/mean}}$
2	$p_{\text{ref,up/dn/mean}}$	$p_{\text{ref,up/dn/mean},j}$	Pa		normal	2	$u(p_{\text{ref},j})$	-1	u_{ref}
3	δp_{zero}	0	Pa	f_0	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{f_0}{2}\right)^2}$	1	u_{zero}
4	$\delta p_{\text{repeat,up/dn/mean}}$	0	Pa	$b'_{\text{up/dn/mean}}$	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{b'}{2}\right)^2}$	1	$u_{\text{repeat,up/dn/mean}}$
5	$\delta p_{\text{hysteresis}}$	0	Pa	h	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{h}{2}\right)^2}$	1	$u_{\text{hysteresis}}$
	Y	$\Delta p_{\text{up/dn/mean}}$	Pa						$u(y)$

Notes: The formulae recommended to determine the quantities f_0, b' and h from a limited set of measured data are defined by equations (21) to (28) in the section *Determination of the characteristic values significant for the uncertainty*.

If sufficient data are available, the repeatability should be expressed by the empirical standard deviation.

For a device with analogue indication, the variability interval $2a$ for No. 1 is equal to $2r$ (refer to Section 6.3).

6.2.2 Calibration of a pressure transducer with electrical output

Choice of the model

Usually the dependence of the output quantity of a pressure transducer (any electrical quantity) on the input quantity (the pressure) is described by a so-called characteristic $Y = \mathrm{f}(p)$, generally a straight line passing through $Y = 0$ or some defined point $Y = Y_0$ and having a slope adjusted by the manufacturer to meet a specified value within certain limits. The calibration of the pressure transducer can now be based on the model equation

$$\Delta Y = Y_{\text{ind}} - \mathrm{f}(p_{\text{ref}}) + \sum \delta Y_i \qquad (15)$$

where the function $\mathrm{f}(p)$ is regarded as defined in the mathematical sense, i.e. in the case of a polynomial by coefficients without uncertainties, and the output quantity Y_{ind} has values y_{ind} measured at the calibration pressures p_{ref} obtained from the standard.

Equation (15) corresponds to equation (8) and the sum/difference model can be used to determine the deviation ΔY and its uncertainty separately for values measured at increasing and decreasing pressure or for the mean values. However, contributions $u(Y_{\text{ind}})$ must be included to account for the measurement uncertainty of the instruments used to measure the output signal of the transducer.

[4] It is recommended to state the unit of the uncertainty contributions (unit of the physical quantity, unit of indication, related (dimensionless) quantity, etc.).

A formally different approach is to determine the transmission coefficient S, using the product/quotient model – again separately for values measured at increasing and decreasing pressures:

$$S_{\text{up/dn}} = \frac{X_{\text{output,up/dn}}}{X_{\text{input}}} = \frac{V_{\text{ind,up/dn}} \; /(GV_{\text{PS}})}{p_{\text{ref,up/dn}}} \prod_{i=1}^{2} K_i$$
$$= \frac{V_{\text{ind,up/dn}} \; /(GV_{\text{PS}})}{p_{\text{ref,up/dn}}} K_{\text{zero}} K_{\text{repeat,up/dn}} \qquad (16)$$

Table 6

$Y = S_{\text{up/dn/mean}}$	measurand; transmission coefficient
$X_1 = V_{\text{ind,up/dn/mean}}$	indication of the output device (voltmeter)
$X_2 = G$	transmission coefficient of amplifier
$X_3 = V_{\text{PS}}$	power supply voltage (auxiliary device)
$X_4 = p_{\text{ref,up/dn/mean}}$	pressure generated by the reference standard
$K_1 = K_{\text{zero}}$	correction factor for zero error
$K_2 = K_{\text{repeat,up/dn/mean}}$	correction factor for repeatability
$K_3 = K_{\text{hysteresis}}$	correction factor for hysteresis
$K_4 = K_{\text{reprod,up/dn/mean}}$	if appropriate, correction factor for reproducibility (for example, when the effect of torque is estimated during the calibration)

The corresponding result for the mean values of the transmission coefficient is obtained by including the correction factor for hysteresis:

$$S_{\text{mean}} = \frac{X_{\text{output,mean}}}{X_{\text{input}}} = \frac{V_{\text{ind,mean}} \; /(GV_{\text{PS}})}{p_{\text{ref,mean}}} \prod_{i=1}^{3} K_i$$
$$= \frac{V_{\text{ind,mean}} \; /(GV_{\text{PS}})}{p_{\text{ref,mean}}} K_{\text{zero}} K_{\text{repeat}} K_{\text{hysteresis}} \qquad (17)$$

Uncertainty calculation

When the increasing and decreasing pressure series are analysed separately, the relative expanded uncertainty (k = 2) of the transmission coefficient is obtained as

$$W(S_{\text{up/dn}}) = k\sqrt{w_{\text{ref}}^2 + w_{\text{ind,up/dn}}^2 + w_G^2 + w_{\text{PS}}^2 + w_{\text{zero}}^2 + w_{\text{repeat,up/dn}}^2} \qquad (18)$$

For the usage of symbols refer also to Table 7.

When the mean value of the increasing and decreasing pressure series is used,

$$W(S_{\text{mean}}) = k\sqrt{w_{\text{ref}}^2 + w_{\text{ind,mean}}^2 + w_{\text{G}}^2 + w_{\text{PS}}^2 + w_{\text{zero}}^2 + w_{\text{repeat,mean}}^2 + w_{\text{hysteresis}}^2} \qquad (19)$$

the largest uncertainty of the repeatabilities repeatabilities $w_{\text{repeat,up/dn}}$ at each calibration pressure is used as the value $w_{\text{repeat,mean}}$.

The relative error span is

$$W'(S_{\text{mean}}) = W_{\text{mean}} + \left| \frac{\Delta S_{\text{mean}}}{S_{\text{mean}}} \right| \qquad (20)$$

$$\text{with } \Delta S_{\text{mean}} = S_{\text{mean}} - S_0$$

The single transmission coefficient S_0 is preferably the slope of the straight line fitted through all measured values of the output signal.

Information available about the input quantities

The knowledge about the input quantities can be summarised in a table:

Table 7

No.	Quantity	Estimate	Unit	Variability interval	Probability distribution	Divisor	Relative standard uncertainty	Exponent associated with X_i	Contribution to uncertainty
	X_i	x_i		$2a$	$P(x_i)$		$w(x_i)$	$c_i x_i y_i^{-1}$	$w_i(y)$
1	$V_{\text{ind,up/dn/mean}}$	$V_{\text{ind,up/dn/mean},j}$	$[V]$		normal	2	$w(V_{\text{ind,up/dn/mean},j})$	1	$w_{\text{ind,up/dn/mean}}$
2	G	G	$[G]$		normal	2	$w(G)$	-1	w_{G}
3	V_{PS}	V_{PS}	$[V]$		normal	2	$w(V_{\text{PS}})$	-1	w_{PS}
4	$p_{\text{ref,up/dn/mean}}$	$p_{\text{ref,up/dn/mean},j}$	Pa		normal	2	$w(p_{\text{ref},j})$	-1	w_{ref}
5	K_{zero}	1	1	$f_{0,\text{rel.}}$	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{f_{0,\text{rel.}}}{2}\right)^2}$	1	w_{zero}
6	$K_{\text{repeat,up/dn/mean}}$	1	1	$b'_{\text{up/dn/mean,rel.}}$	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{b'_{\text{rel.}}}{2}\right)^2}$	1	$w_{\text{repeat,up/dn/mean}}$
7	$K_{\text{reprod,up/dn/mean}}$	1	1	$b_{\text{up/dn/mean,rel.}}$	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{b_{\text{rel.}}}{2}\right)^2}$	1	$w_{\text{reprod,up/dn/mean}}$
8	$K_{\text{hysteresis}}$	1	1	$h_{\text{rel.}}$	rectangular	$\sqrt{3}$	$\sqrt{\frac{1}{3}\left(\frac{h_{\text{rel.}}}{2}\right)^2}$	1	$w_{\text{hysteresis}}$
	Y	$S_{\text{up/dn/mean}}$	$[S]$						$w(y)$

Notes: The characteristic quantities $f_{0,\text{rel.}}$, $b'_{\text{rel.}}$, $b_{\text{rel.}}$ and $h_{\text{rel.}}$ here are *relative* quantities, i.e. quantities related to the measured value (the indication).

In the determination of the transmission factor, the zero point is *not* a calibration point. Despite this, the zero shift observed enters into the uncertainty of the measured values of the output signal and thus influences the uncertainty of the calibration result for the output quantity *S*.

See also notes to Table 5

6.3 Determination of the characteristic values significant for the uncertainty

Preliminary remark: According to page 17, the type A contributions to the uncertainty should be stated in the form of empirical standard deviations. In the case of measuring instruments affected by hysteresis, where the measurements in the direction of increasing and decreasing pressures must be evaluated separately, a maximum of only three measured values is available at each calibration point and the assumption that these values are normally distributed is often not justified. Some simple formulae are, therefore, given in the following. They are not based on statistical assumptions and, according to experience, they furnish useful substitutes for the standard deviations. Their application is, however, optional.

Resolution *r*

For devices with digital indication the resolution corresponds to the digit step, provided the indicated value does not vary by more than one digit step when the pressure-measuring device is unloaded. A variability interval $2a = r$ of a rectangular distribution is to be estimated.

If, with the pressure-measuring device unloaded, the indicated value varies by more than the value of the resolution determined before, the resolution r is to be taken as the span of the fluctuation, additionally added with a digital step.

For devices with analogue indication the indicated value is estimated by visual interpolation between any two successive scale marks. Thus, the smallest assessable division of the scale interval is called the interpolated division r, differentiating between different values indicated. For the uncertainty analysis a variability interval $2a = 2r$ of a rectangular distribution is to be estimated.

Zero error f_0

The zero point *may* be set prior to each measurement cycle comprising one measurement series each at increasing and decreasing pressures, and it *must* be recorded prior to and after each measurement cycle. The reading in units of pressure – when indicated after conversion – must be taken after the complete removal of the load. The zero error is calculated as follows:

$$f_0 = \max\{|p_{ind,2,0} - p_{ind,1,0} - (p_{ref,2,0} - p_{ref1,0})|, |p_{ind,4,0} - p_{ind,3,0} - (p_{ref,4,0} - p_{ref3,0})|, |p_{ind,6,0} - p_{ind,5,0} - (p_{ref,6,0} - p_{ref5,0})|\} \quad (21)$$

The indices number the measured values $p_{ind,i,j}$ read at the zero points $j = 0$ of measurement series M1 to M6 with $i = 1$ to 6.

Repeatability *b′*

The repeatability, with the mounting unchanged, is determined from the difference between the deviations measured in the corresponding measurement series, corrected by the zero signal (the index j numbers the nominal pressure values):

$$b'_{up,j} = \max\{|(p_{ind,3,j} - p_{ind,3,0}) - (p_{ind,1,j} - p_{ind,1,0}) - (p_{ref,3,j} - p_{ref,3,0}) + (p_{ref,1,j} - p_{ref,1,0})|, |(p_{ind,5,j} - p_{ind,5,0}) - (p_{ind,1,j} - p_{ind,1,0}) - (p_{ref,5,j} - p_{ref,5,0}) + (p_{ref,1,j} - p_{ref,1,0})|, |(p_{ind,5,j} - p_{ind,5,0}) - (p_{ind,3,j} - p_{ind,3,0}) - (p_{ref,5,j} - p_{ref,5,0}) + (p_{ref,3,j} - p_{ref,3,0})|\} \quad (22a)$$

$$b'_{dn,j} = \max\{|(p_{ind,4,j} - p_{ind,3,0}) - (p_{ind,2,j} - p_{ind,1,0}) - (p_{ref,4,j} - p_{ref,3,0}) + (p_{ref,2,j} - p_{ref,1,0})|, |(p_{ind,6,j} - p_{ind,5,0}) - (p_{ind,2,j} - p_{ind,1,0}) - (p_{ref,6,j} - p_{ref,5,0}) + (p_{ref,2,j} - p_{ref,1,0})|, |(p_{ind,6,j} - p_{ind,5,0}) - (p_{ind,4,j} - p_{ind,3,0}) - (p_{ref,6,j} - p_{ref,5,0}) + (p_{ref,4,j} - p_{ref,3,0})|\} \quad (23a)$$

$$b'_{mean,j} = \max\{b'_{up,j}, b'_{dn,j}\} \quad (24)$$

The equations (22a) and (23a) are replaced with (22b) and (23b)

$$b'_{up,j} = |(p_{ind,3,j} - p_{ind,3,0}) - (p_{ind,1,j} - p_{ind,1,0}) - (p_{ref,3,j} - p_{ref,3,0}) + (p_{ref,1,j} - p_{ref,1,0})| \quad (22b)$$

$$b'_{dn,j} = |(p_{ind,4,j} - p_{ind,3,0}) - (p_{ind,2,j} - p_{ind,1,0}) - (p_{ref,4,j} - p_{ref,3,0}) + (p_{ref,2,j} - p_{ref,1,0})| \quad (23b)$$

if the third series of measurements is performed after reinstallation to check reproducibility.

Reproducibility *b*

The reproducibility, with the mounting changed by reinstallation, is determined from the difference between the values measured in the corresponding measurement series, corrected by the zero signal:

$b_{up,j}$ = max{|($p_{ind,5,j}$ – $p_{ind,5,0}$) – ($p_{ind,1,j}$ – $p_{ind,1,0}$) – ($p_{ref,5,j}$ – $p_{ref,5,0}$) + ($p_{ref,1,j}$ – $p_{ref,1,0}$)|,|($p_{ind,5,j}$ – $p_{ind,5,0}$) – ($p_{ind,3,j}$ – $p_{ind,3,0}$) – ($p_{ref,5,j}$ – $p_{ref,5,0}$) + ($p_{ref,3,j}$ – $p_{ref,3,0}$)|} (25)

$b_{dn,j}$ = max{|($p_{ind,6,j}$ – $p_{ind,5,0}$) – ($p_{ind,2,j}$ – $p_{ind,1,0}$) – ($p_{ref,6,j}$ – $p_{ref,5,0}$) + ($p_{ref,2,j}$ – $p_{ref,1,0}$)|, |($p_{ind,6,j}$ – $p_{ind,5,0}$) – ($p_{ind,4,j}$ – $p_{ind,3,0}$) – ($p_{ref,6,j}$ – $p_{ref,5,0}$) + ($p_{ref,4,j}$ – $p_{ref,3,0}$)|} (26)

$b_{mean,j}$ = max{$b_{up,j}$, $b_{dn,j}$} (27)

Hysteresis *h* (Reversibility)

The hysteresis is determined from the difference between the corresponding deviations of the output values measured at increasing and decreasing pressures, corrected by the zero signal:

$$h_j = \frac{1}{n}\sum_{m=1}^{n}\left|\left(p_{\text{ind},2m,j} - p_{\text{ind},2m-1,0}\right) - \left(p_{\text{ind},2m-1,j} - p_{\text{ind},2m-1,0}\right) - \left(p_{\text{ref},2m,j} - p_{\text{ref},2m-1,0}\right) + \left(p_{\text{ref},2m-1,j} - p_{\text{ref},2m-1,0}\right)\right| \quad (28)$$

The variable *n* refers to the number of the complete measuring cycles *m*.

7 EXAMPLES

General remarks

Two examples have been chosen:

Example 1: Calibration of an indicating digital pressure gauge with oil as the pressure medium. The three different calibration procedures referring to Section 5.2 are presented:

(a) Basic Calibration Procedure (Example 1a),

(b) Standard Calibration Procedure (Example 1b),

(c) Comprehensive Calibration Procedure (Example 1c).

Example 2: Calibration of a pressure transducer with oil as the pressure medium. Example 2 is evaluated in two different ways:

(a) by using a linear characteristic to model the output signal (Example 2a),

(b) by determining the transmission coefficient (Example 2b).

In these examples it is assumed that the pressures generated by the reference standard, p_{ref}, were exactly the same in the series measured at increasing and decreasing pressures as well as in repeated measurement series. If it is not the case, individual reference pressure values must be taken for each measurement series.

7.1 Example 1 – Calibration of an indicating digital pressure gauge

Calibration object

The calibration oject was an indicating digital pressure gauge with the following parameters:

Range:	0 MPa to 25 MPa (gauge pressure)
Resolution	0.1 kPa
Reference temperature:	20 °C

Note: At pressures below some small critical value, the zero reading appears in the display. The zero reading does not correspond exactly to p_{ref} = 0.

Reference standard

The reference standard was an oil-operated pressure balance operated at piston-cylinder temperature t_{ref}, at ambient pressure p_{amb} and ambient temperature t_{amb}, i.e. at an ambient air density $\rho_{amb}(p_{amb}, t_{amb}$, 60 % relative humidity).

The expanded uncertainty of the pressures measured at calibration conditions in the reference level of the calibration object is

$$U(p_{ref}) = 0.02\,\text{kPa} + 8.0 \cdot 10^{-5} \cdot p_{ref} \text{ for } p_{ref} > 1\text{ MPa}$$

Calibration procedure

Before calibration the instrument was twice brought to its nominal pressure and kept at this pressure for one minute.

The difference Δh in height between the pressure reference levels of the calibration object and the standard instrument was adjusted to zero.

The calibration temperature was equal to the reference temperature within ±0.5 °C.

Depending on the chosen calibration procedure, one or three complete cycles of comparison measurements were carried out. In the case of the Basic and Standard Calibration Procedures, additional measurements were carried out for determining the repeatability as described. Tables E1a.1, E1b.1 and E1c.1 show the raw data. The evaluation of the data is given in Tables E1a.2, E1b.2 and E1c.2. Finally, the uncertainty analyses for a selected reference pressure are presented in Tables E1a.3, E1b.3 and E1c.3. The numerical results for the Comprehensive Calibration Procedure are depicted in Figure 7.

Evaluation of the uncertainty of measurement

The uncertainty of the observed difference between the indicated pressure and the reference pressure as obtained from the reference standard is calculated from the sum/difference model separately for pressures measured at increasing and decreasing pressures. The uncertainty of the mean values of the indicated pressure is calculated by adding the uncertainty contribution due to reversibility (hysteresis). If no corrections are applied to the readings, the accuracy of the pressures measured with the calibrated instrument is given by its error span.

7.1.1 Example 1a – Basic calibration procedure

Table E1a.1: Raw data

Applied pressure	Expanded uncertainty	Reading p_{ind}					
p_{ref}	$U(p_{ref})$	M1 (up)	M2 (dn)	M3 (up)		M5 (up)	
bar	bar	bar	bar	bar		bar	
0.000	0.0000	-0.079	-0.076	-0.084		-0.071	
50.029	0.0042	49.934	49.974				
100.057	0.0082	99.972	100.005				
150.085	0.0122	150.038	150.046	150.006		150.018	
200.113	0.0162	200.088	200.075				
250.140	0.0202	250.098	250.108				

Table E1a.2: Calculation and results

Expanded uncertainty	Applied pressure	Applied pressure	Reading	Repeatability interval		Devia-tion	Expanded uncertainty of measurement[5]	
$U(p_{ref})$	p_{ref}	p_{ref}	$p_{ind,up/dn}$	$b'_{up/dn}$		$\Delta p_{up/dn}$	$U(\Delta p_{up/dn})$	
kPa	MPa	bar	bar	bar		bar	bar	
0.00	0.0000	0.000	-0.079	0.028		-0.079	0.016	
0.42	5.0029	50.029	49.934	0.028		-0.095	0.017	
0.82	10.0057	100.057	99.972	0.028		-0.085	0.018	
1.22	15.0085	150.085	150.038	0.028		-0.047	0.020	
1.62	20.0113	200.113	200.088	0.028		-0.025	0.023	
2.02	25.0140	250.140	250.098	0.028		-0.042	0.026	
2.02	25.0140	250.140	250.108	0.028		-0.032	0.026	
1.62	20.0113	200.113	200.075	0.028		-0.038	0.023	
1.22	15.0085	150.085	150.046	0.028		-0.039	0.020	
0.82	10.0057	100.057	100.005	0.028		-0.052	0.018	
0.42	5.0029	50.029	49.974	0.028		-0.055	0.017	
0.00	0.0000	0.000	-0.076	0.028		-0.076	0.016	

[5] The stated values for $U(\Delta p_{up/dn})$ are only calculative results from the uncertainty analysis and not applicable for reporting. Due to the chosen Basic Calibration Procedure, the expanded uncertainties are not smaller than 0.2 % FS. Thus, for the whole calibration range $U(\Delta p_{up/dn})$ = 0.50 bar is valid.

Expanded uncertainty	Applied pressure	Applied pressure	Mean reading	Repeatability interval	Hyster-esis	Devia-tion	Expanded uncertainty of measurement[6]	Error span
$U(p_{ref})$	p_{ref}	p_{ref}	$p_{ind,mean}$	b'_{mean}	h	Δp_{mean}	$U(\Delta p_{mean})$	$U'(\Delta p_{mean})$
kPa	MPa	bar	bar	bar	bar	bar	bar	bar
0.00	0.0000	0.000	-0.078	0.028	0.003	-0.078	0.016	0.578
0.42	5.0029	50.029	49.954	0.028	0.040	-0.075	0.029	0.575
0.82	10.0057	100.057	99.989	0.028	0.033	-0.069	0.026	0.569
1.22	15.0085	150.085	150.042	0.028	0.008	-0.043	0.021	0.543
1.62	20.0113	200.113	200.082	0.028	0.013	-0.031	0.024	0.531
2.02	25.0140	250.140	250.103	0.028	0.010	-0.037	0.027	0.537

Table E1a.3: Uncertainty budget at calibration pressure 100 bar

Quantity	Estimate	Variability interval	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty	Variance
X_i	x_i	$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$
p_{ref}	100.057 bar	0.0164 bar	normal	2	0.0041 bar	-1	0.0041 bar	$1.68\cdot10^{-5}$ bar^2
$p_{ind.mean}$	99.989 bar	0.0010 bar	rectangular	$\sqrt{3}$	$2.89\cdot10^{-4}$ bar	1	$2.89\cdot10^{-4}$ bar	$8.33\cdot10^{-8}$ bar^2
δp_{zero}	0.000 bar	0.0030 bar	rectangular	$\sqrt{3}$	$8.66\cdot10^{-4}$ bar	1	$8.66\cdot10^{-4}$ bar	$7.50\cdot10^{-7}$ bar^2
$\delta p_{repeat.mean}$	0.000 bar	0.0280 bar	rectangular	$\sqrt{3}$	0.0081 bar	1	0.0081 bar	$6.53\cdot10^{-5}$ bar^2
$\delta p_{hysteresis}$	0.000 bar	0.0330 bar	rectangular	$\sqrt{3}$	0.0095 bar	1	0.0095 bar	$9.08\cdot10^{-5}$ bar^2
Δp_{mean}	-0.069 bar						0.0132 bar	$1.74\cdot10^{-4}$ bar^2
Δp_{mean} = -0.07 bar		**Due to the chosen Basic Calibration Procedure, the expanded uncertainty is not smaller than 0.2 % FS.**					**$U(\Delta p_{mean})$ = 0.50 bar at k = 2**	

[6] The stated values for $U(\Delta p_{mean})$ are only calculative results from the uncertainty analysis and not applicable for reporting. Due to the chosen Basic Calibration Procedure, the expanded uncertainties are not smaller than 0.2 % FS. Thus, for the whole calibration range $U(\Delta p_{mean})$ = 0.50 bar is valid. The error span $U'(\Delta p_{mean})$ is calculated on the basis of the valid uncertainty.

7.1.2 Example 1b – Standard calibration procedure

Table E1b.1: Raw data

Applied pressure	Expanded uncertainty	Reading p_{ind}					
p_{ref}	$U(p_{ref})$	M1 (up)	M2 (dn)	M3 (up)		M5 (up)	
bar	bar	bar	bar	bar		bar	
0.000	0.0000	-0.079	-0.076	-0.084		-0.071	
25.015	0.0022	24.943	24.931				
50.029	0.0042	49.934	49.974	49.967		49.956	
75.043	0.0062	74.940	74.960				
100.057	0.0082	99.972	100.005				
125.071	0.0102	125.019	125.031	124.994		124.974	
150.085	0.0122	150.038	150.046				
175.099	0.0142	175.004	175.051				
200.113	0.0162	200.088	200.075	200.033		200.078	
225.127	0.0182	225.079	225.064				
250.140	0.0202	250.098	250.108				

Table E1b.2: Calculation and results

Expanded uncertainty	Applied pressure	Applied pressure	Reading	Repeatability interval		Devia-tion	Expanded uncertainty of measurement[7]	
$U(p_{\text{ref}})$	p_{ref}	p_{ref}	$p_{\text{ind,up/dn}}$	$b'_{\text{up/dn}}$		$\Delta p_{\text{up/dn}}$	$U(\Delta p_{\text{up/dn}})$	
kPa	MPa	bar	bar	bar		bar	bar	
0.00	0.0000	0.000	-0.079	0.000		-0.079	0.002	
0.22	2.5015	25.015	24.943	0.038		-0.072	0.022	
0.42	5.0029	50.029	49.934	0.038		-0.095	0.022	
0.62	7.5043	75.043	74.940	0.053		-0.103	0.031	
0.82	10.0057	100.057	99.972	0.053		-0.085	0.032	
1.02	12.5071	125.071	125.019	0.053		-0.052	0.032	
1.22	15.0085	150.085	150.038	0.053		-0.047	0.033	
1.42	17.5099	175.099	175.004	0.053		-0.095	0.034	
1.62	20.0113	200.113	200.088	0.050		-0.025	0.033	
1.82	22.5127	225.127	225.079	0.050		-0.048	0.034	
2.02	25.0140	250.140	250.098	0.050		-0.042	0.035	
2.02	25.0140	250.140	250.108	0.050		-0.032	0.035	
1.82	22.5127	225.127	225.064	0.050		-0.063	0.034	
1.62	20.0113	200.113	200.075	0.050		-0.038	0.033	
1.42	17.5099	175.099	175.051	0.053		-0.048	0.034	
1.22	15.0085	150.085	150.046	0.053		-0.039	0.033	
1.02	12.5071	125.071	125.031	0.053		-0.040	0.032	
0.82	10.0057	100.057	100.005	0.053		-0.052	0.032	
0.62	7.5043	75.043	74.960	0.053		-0.083	0.031	
0.42	5.0029	50.029	49.974	0.038		-0.055	0.022	
0.22	2.5015	25.015	24.931	0.038		-0.084	0.022	
0.00	0.0000	0.000	-0.076	0.000		-0.076	0.002	

[7] The stated values for $U(\Delta p_{\text{up/dn}})$ are only calculative results from the uncertainty analysis and not applicable for reporting. Due to the chosen Standard Calibration Procedure, the expanded uncertainties are not to be smaller than 0.05 % FS. Thus, for the whole calibration range $U(\Delta p_{\text{up/dn}})$ = 0.13 bar is valid.

Expanded uncertainty	Applied pressure	Applied pressure	Mean reading	Repeatability interval	Hyster-esis	Devia-tion	Expanded uncertainty of measurement[8]	Error span
$U(p_{ref})$	p_{ref}	p_{ref}	$p_{ind,mean}$	b'_{mean}	h	Δp_{mean}	$U(\Delta p_{mean})$	$U'(\Delta p_{mean})$
kPa	MPa	bar	bar	bar	bar	bar	bar	bar
0.00	0.0000	0.000	-0.078	0.000	0.003	-0.078	0.003	0.203
0.22	2.5015	25.015	24.937	0.038	0.012	-0.078	0.023	0.203
0.42	5.0029	50.029	49.954	0.038	0.040	-0.075	0.032	0.200
0.62	7.5043	75.043	74.950	0.053	0.020	-0.093	0.033	0.218
0.82	10.0057	100.057	99.989	0.053	0.033	-0.069	0.037	0.194
1.02	12.5071	125.071	125.025	0.053	0.012	-0.046	0.033	0.171
1.22	15.0085	150.085	150.042	0.053	0.008	-0.043	0.033	0.168
1.42	17.5099	175.099	175.028	0.053	0.047	-0.072	0.043	0.197
1.62	20.0113	200.113	200.082	0.050	0.013	-0.031	0.034	0.156
1.82	22.5127	225.127	225.072	0.050	0.015	-0.055	0.035	0.180
2.02	25.0140	250.140	250.103	0.050	0.010	-0.037	0.036	0.162

Table E1b.3: Uncertainty budget at calibration pressure 100 bar

Quantity	Estimate	Variability interval	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty	Variance
X_i	x_i	$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$
p_{ref}	100.057 bar	0.0164 bar	normal	2	0.0041 bar	-1	0.0041 bar	$1.68\cdot10^{-5}$ bar²
$p_{ind.mean}$	99.989 bar	0.0010 bar	rectangular	$\sqrt{3}$	$2.89\cdot10^{-4}$ bar	1	$2.89\cdot10^{-4}$ bar	$8.33\cdot10^{-8}$ bar²
δp_{zero}	0.000 bar	0.0030 bar	rectangular	$\sqrt{3}$	$8.66\cdot10^{-4}$ bar	1	$8.66\cdot10^{-4}$ bar	$7.50\cdot10^{-7}$ bar²
$\delta p_{repeat.mean}$	0.000 bar	0.0530 bar	rectangular	$\sqrt{3}$	0.0153 bar	1	0.0153 bar	$2.34\cdot10^{-4}$ bar²
$\delta p_{hysteresis}$	0.000 bar	0.0330 bar	rectangular	$\sqrt{3}$	0.0095 bar	1	0.0095 bar	$9.08\cdot10^{-5}$ bar²
Δp_{mean}	-0.069 bar						0.0185 bar	$3.42\cdot10^{-4}$ bar²
Δp_{mean} = -0.07 bar	**Due to the chosen Standard Calibration Procedure, the expanded uncertainty is not smaller than 0.05 % FS.**						**$U(\Delta p_{mean})$ = 0.13 bar at k = 2**	

[8] The stated values for $U(\Delta p_{mean})$ are only calculative results from the uncertainty analysis and not applicable for reporting. Due to the chosen Standard Calibration Procedure, the expanded uncertainties are not to be smaller than 0.05 % FS. Thus, for the whole calibration range $U(\Delta p_{mean})$ = 0.13 bar is valid. The error span $U'(\Delta p_{mean})$ is calculated on the basis of the valid uncertainty.

7.1.3 Example 1c – Comprehensive Calibration Procedure

Table E1c.1: Raw data

Applied pressure	Expanded uncertainty	Reading p_{ind}					
p_{ref}	$U(p_{ref})$	M1 (up)	M2 (dn)	M3 (up)	M4 (dn)	M5 (up)	M6 (dn)
bar	bar	bar	bar	bar	bar	bar	bar
0.000	0.0000	-0.079	-0.076	-0.084	-0.067	-0.071	-0.078
25.015	0.0022	24.943	24.931	24.898	24.958	24.952	24.946
50.029	0.0042	49.934	49.974	49.967	49.997	49.956	49.975
75.043	0.0062	74.940	74.960	74.957	74.994	74.971	74.983
100.057	0.0082	99.972	100.005	99.985	99.981	99.991	100.016
125.071	0.0102	125.019	125.031	124.994	125.018	124.974	125.001
150.085	0.0122	150.038	150.046	150.006	150.061	150.018	150.025
175.099	0.0142	175.004	175.051	175.038	175.062	175.045	175.061
200.113	0.0162	200.088	200.075	200.033	200.061	200.078	200.027
225.127	0.0182	225.079	225.064	225.044	225.102	225.069	225.079
250.140	0.0202	250.098	250.108	250.084	250.072	250.052	250.077

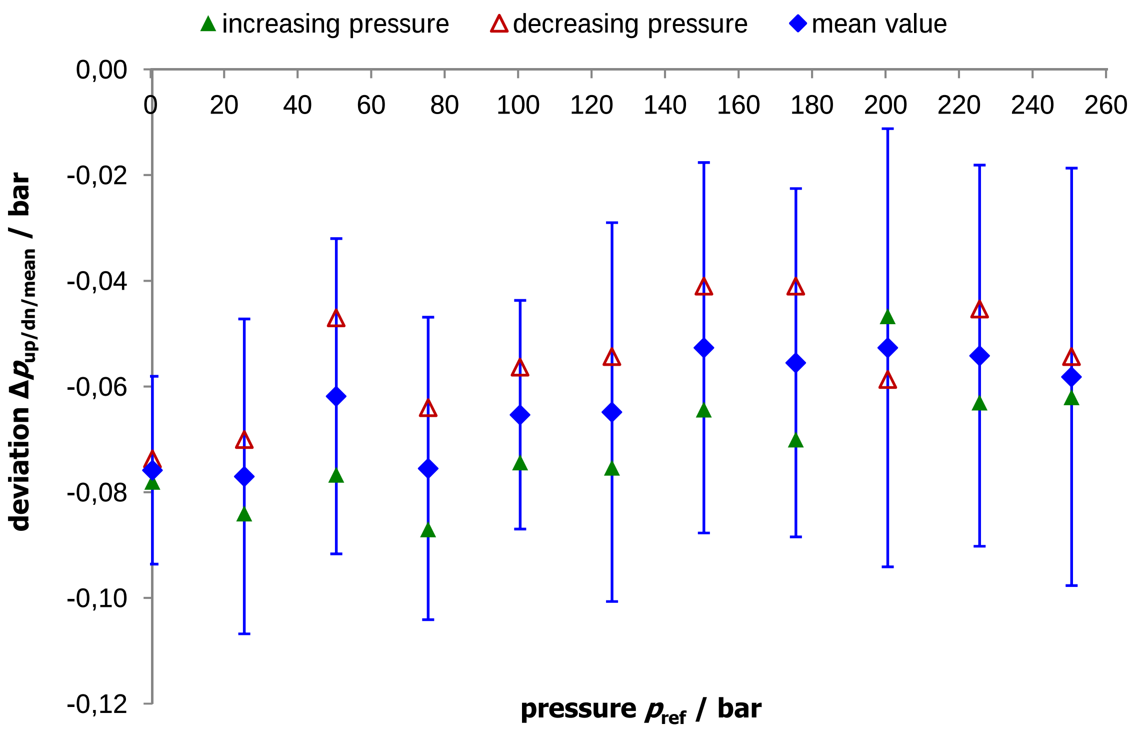
Table E1c.2: Calculation and results

Expanded uncertainty	Applied pressure	Applied pressure	Mean reading	Repeatability interval		Devia-tion	Expanded uncertainty of measurement	
$U(p_{ref})$	p_{ref}	p_{ref}	$p_{ind,up/dn}$	$b'_{up/dn}$		$\Delta p_{up/dn}$	$U(\Delta p_{up/dn})$	
kPa	MPa	bar	bar	bar		bar	bar	
0.00	0.0000	0.000	-0.078	0.000		-0.078	0.010	
0.22	2.5015	25.015	24.931	0.041		-0.084	0.026	
0.42	5.0029	50.029	49.952	0.038		-0.077	0.024	
0.62	7.5043	75.043	74.956	0.023		-0.087	0.018	
0.82	10.0057	100.057	99.983	0.018		-0.074	0.016	
1.02	12.5071	125.071	124.996	0.053		-0.075	0.034	
1.22	15.0085	150.085	150.021	0.028		-0.064	0.023	
1.42	17.5099	175.099	175.029	0.039		-0.070	0.028	
1.62	20.0113	200.113	200.066	0.050		-0.047	0.035	
1.82	22.5127	225.127	225.064	0.030		-0.063	0.027	
2.02	25.0140	250.140	250.078	0.054		-0.062	0.038	
2.02	25.0140	250.140	250.086	0.039		-0.054	0.032	
1.82	22.5127	225.127	225.082	0.043		-0.045	0.032	
1.62	20.0113	200.113	200.054	0.056		-0.059	0.037	
1.42	17.5099	175.099	175.058	0.016		-0.041	0.020	
1.22	15.0085	150.085	150.044	0.049		-0.041	0.032	
1.02	12.5071	125.071	125.017	0.038		-0.054	0.026	
0.82	10.0057	100.057	100.001	0.022		-0.056	0.018	
0.62	7.5043	75.043	74.979	0.039		-0.064	0.025	
0.42	5.0029	50.029	49.982	0.035		-0.047	0.023	
0.22	2.5015	25.015	24.945	0.032		-0.070	0.021	
0.00	0.0000	0.000	-0.074	0.024		-0.074	0.017	

Expanded uncertainty	Applied pressure	Applied pressure	Mean reading	Repeatability interval	Hyster-esis	Devia-tion	Expanded uncertainty of measurement	Error span
$U(p_{ref})$	p_{ref}	p_{ref}	$p_{ind,mean}$	b'_{mean}	h	Δp_{mean}	$U(\Delta p_{mean})$	$U'(\Delta p_{mean})$
kPa	MPa	bar	bar	bar	bar	bar	bar	bar
0.00	0.0000	0.000	-0.076	0.024	0.009	-0.076	0.018	0.094
0.22	2.5015	25.015	24.938	0.041	0.026	-0.077	0.030	0.107
0.42	5.0029	50.029	49.967	0.038	0.030	-0.062	0.030	0.092
0.62	7.5043	75.043	74.968	0.039	0.023	-0.076	0.029	0.104
0.82	10.0057	100.057	99.992	0.022	0.021	-0.065	0.022	0.087
1.02	12.5071	125.071	125.006	0.053	0.021	-0.065	0.036	0.101
1.22	15.0085	150.085	150.032	0.049	0.023	-0.053	0.035	0.088
1.42	17.5099	175.099	175.044	0.039	0.029	-0.055	0.033	0.088
1.62	20.0113	200.113	200.060	0.056	0.031	-0.053	0.041	0.094
1.82	22.5127	225.127	225.073	0.043	0.028	-0.054	0.036	0.090
2.02	25.0140	250.140	250.082	0.054	0.016	-0.058	0.039	0.098

Table E1c.3: Uncertainty budget at calibration pressure 100 bar

Quantity	Estimate	Variability interval	Probability distribution	Divi-sor	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty	Variance
X_i	x_i	$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$
p_{ref}	100.057 bar	0.0164 bar	normal	2	0.0041 bar	-1	0.0041 bar	$1.68 \cdot 10^{-5}$ bar^2
$p_{ind,mean}$	99.992 bar	0.0010 bar	rectangular	$\sqrt{3}$	$2.89 \cdot 10^{-4}$ bar	1	$2.89 \cdot 10^{-4}$ bar	$8.33 \cdot 10^{-8}$ bar^2
δp_{zero}	0.000 bar	0.0170 bar	rectangular	$\sqrt{3}$	0.0049 bar	1	0.0049 bar	$2.41 \cdot 10^{-5}$ bar^2
$\delta p_{repeat,mean}$	0.000 bar	0.0220 bar	rectangular	$\sqrt{3}$	0.0064 bar	1	0.0064 bar	$4.03 \cdot 10^{-5}$ bar^2
$\delta p_{hysteresis}$	0.000 bar	0.0207 bar	rectangular	$\sqrt{3}$	0.0060 bar	1	0.0060 bar	$3.56 \cdot 10^{-5}$ bar^2
Δp_{mean}	-0.065 bar						0.0108 bar	$1.17 \cdot 10^{-4}$ bar^2
Δp_{mean} = -0.065 bar	**$U(\Delta p_{mean}) = k \cdot u(\Delta p_{mean})$ (k = 2)**						**$U(\Delta p_{mean})$ = 0.022 bar**	



The error bars indicate the expanded uncertainty of mean values.

Figure 7 – Calibration of an indicating pressure gauge using the Comprehensive Calibration Procedure – Example 1c

7.2 Example 2 – Calibration of a pressure transducer

Calibration object

The calibration object was a pressure transducer with a Wheatstone bridge on a metal diaphragm as the sensing element. It had the following parameters:

Range: 0 MPa to 20 mPa (gauge pressure)

Reference temperature: 20 °C.

Reference standard

The reference standard was an oil-operated pressure balance operated at piston-cylinder temperature t_{ref}, at ambient pressure p_{amb} and ambient temperature t_{amb}, i.e. at an ambient air density $\rho_{amb}(p_{amb}, t_{amb}$, 60 % rel. humidity).

The expanded uncertainty of the pressures measured at calibration conditions in the reference level of the calibration object is

$$U(p_{ref}) = 1.0 \cdot 10^{-4} \cdot p_{ref} \quad \text{for } p_{ref} > 1 \text{ MPa}$$

Calibration procedure

The output signal of the pressure transducer was measured as $I_{ind} \equiv V_{ind} / (G \cdot V_{PS})$ in units mV/V using a digital compensator, the expanded measurement uncertainty of which was 0.00005 mV/V.

Before calibration the instrument was twice brought to its maximum pressure and kept at this pressure for one minute.

The difference Δh in height between the pressure reference levels of the calibration object and the standard instrument was adjusted to zero.

The calibration temperature was equal to the reference temperature within ±0.5 °C.

Three complete cycles of comparison measurements were carried out (Comprehensive Calibration Procedure). To check the reproducibility the pressure transducer was reinstalled before starting the third measuring cycle. Table E2 shows the raw data.

Table E2: Raw data

Applied pressure	Relative expanded uncertainty	Indication of the digital compensator I_{ind}					
p_{ref}	$W(p_{ref})$	M1 (up)	M2 (dn)	M3 (up)	M4 (dn)	M5 (up)	M6 (dn)
bar		mV/V	mV/V	mV/V	mV/V	mV/V	mV/V
0.000		0.00000	-0.00003	0.00000	0.00002	0.00000	-0.00002
20.010	$1.0 \cdot 10^{-4}$	0.20009	0.20026	0.20019	0.20033	0.20021	0.20032
40.022	$1.0 \cdot 10^{-4}$	0.40026	0.40063	0.40032	0.40067	0.40033	0.40064
60.033	$1.0 \cdot 10^{-4}$	0.60041	0.60094	0.60049	0.60097	0.60049	0.60092
80.045	$1.0 \cdot 10^{-4}$	0.80053	0.80118	0.80062	0.80120	0.80062	0.80110
100.056	$1.0 \cdot 10^{-4}$	1.00063	1.00139	1.00072	1.00135	1.00075	1.00125
120.068	$1.0 \cdot 10^{-4}$	1.20074	1.20149	1.20080	1.20141	1.20082	1.20132
140.079	$1.0 \cdot 10^{-4}$	1.40080	1.40158	1.40089	1.40150	1.40090	1.40133
160.091	$1.0 \cdot 10^{-4}$	1.60082	1.60157	1.60091	1.60148	1.60091	1.60126
180.102	$1.0 \cdot 10^{-4}$	1.80084	1.80148	1.80097	1.80135	1.80091	1.80111
200.113	$1.0 \cdot 10^{-4}$	2.00079	2.00100	2.00088	2.00114	2.00086	2.00087

The evaluation of Example 2a is based on the defined linear characteristic of the instrument. The pressures calculated from the measured output signals using this characteristic are compared with the pressures obtained from the standard instrument. The sum/difference model is applied to calculate the uncertainty of measurement using procedures described in Section 6.3 "Determination of the characteristic values significant for the uncertainty" (page 22). The numerical results are presented in Table E2a.1 and are depicted in Figure 8.

In Example 2b, the transmission coefficient of the same instrument is determined at the same calibration points. Zero error, repeatability, reproducibility and hysteresis are calculated using the formulae presented on page 23 each divided by the corresponding indication I_{ind} to obtain the relative values. The numerical results are presented in Tables E2b.1 and E2b.2 and are shown in Figure 9.

Figure 8 demonstrates that the calibration methods 2a and 2b are equivalent.

The error spans $U'(\Delta p_{mean})$ plotted in Figure 8 can be calculated from the error spans $U'(S_{mean})$ of the values of the transmission coefficient S_{mean} as

$$U'(\Delta p_{mean}) = U'(S_{mean}) \cdot p_{ref} \cdot (1/S_0) = W'(S_{mean}) \cdot p_{ref}$$

Evaluation of the uncertainty of measurement

The uncertainty of the observed difference Δp between the pressure calculated from the characteristic straight line and the reference pressure as obtained from the reference standard is calculated from the sum/difference model separately for pressures measured at increasing and decreasing pressures. The uncertainty of the mean values of Δp is calculated by adding the uncertainty contribution due to reversibility (hysteresis). If no corrections are applied to the readings, the accuracy of the pressures measured with the calibrated instrument is given by its error span.

Note: The slope of the linear characteristic, the single transmission coefficient S_0, is obtained from a straight line fitted to the calibration data. It replaces the nominal value $1.000000 \cdot 10^{-2}$ (mV/V)/bar (corresponding to an output signal of 2 mV/V FS) as defined by the manufacturer and – like the nominal value – has to be regarded as a *defined value* without uncertainty.

7.2.1 Example 2a – Modelling the output signal by using a linear characteristic

Table E2a.1: Calculation and results

Expanded uncer-tainty	Applied pressure	Applied pressure	Mean indication	Repeat-ability interval	Reprodu-cibility interval	Expanded uncertainty of digital compensator	Modelled indicated pressure	Devia-tion	Expanded uncertainty of measure-ment
$U(p_{ref})$	p_{ref}	p_{ref}	$I_{ind,up/dn}$	$b'_{up/dn}$	$b_{up/dn}$	$U(V_{ind,up/dn})$	$p_{ind,mod,up/dn}$	$\Delta p_{up/dn}$	$U(\Delta p_{up/dn})$
kPa	MPa	bar	mV/V	mV/V	mV/V	mV/V	bar	bar	bar
0.00	0.0000	0.000	0.000000	0.000000	0.000000	0.000050	0.000	0.000	0.005
0.20	2.0010	20.010	0.200163	0.000100	0.000120	0.000050	20.013	0.003	0.011
0.40	4.0022	40.022	0.400303	0.000060	0.000070	0.000050	40.024	0.002	0.009
0.60	6.0033	60.033	0.600463	0.000080	0.000080	0.000050	60.037	0.004	0.010
0.80	8.0045	80.045	0.800590	0.000090	0.000090	0.000050	80.047	0.002	0.012
1.00	10.0056	100.056	1.000700	0.000090	0.000120	0.000050	100.055	-0.001	0.014
1.20	12.0068	120.068	1.200787	0.000060	0.000080	0.000050	120.061	-0.007	0.014
1.40	14.0079	140.079	1.400863	0.000090	0.000100	0.000050	140.065	-0.014	0.017
1.60	16.0091	160.091	1.600880	0.000090	0.000090	0.000050	160.064	-0.027	0.018
1.80	18.0102	180.102	1.800907	0.000130	0.000070	0.000050	180.063	-0.039	0.021
2.00	20.0113	200.113	2.000843	0.000090	0.000070	0.000050	200.054	-0.059	0.022
2.00	20.0113	200.113	2.001003	0.000140	0.000270	0.000050	200.070	-0.043	0.027
1.80	18.0102	180.102	1.801313	0.000130	0.000370	0.000050	180.104	0.002	0.029
1.60	16.0091	160.091	1.601437	0.000090	0.000310	0.000050	160.119	0.028	0.025
1.40	14.0079	140.079	1.401470	0.000080	0.000250	0.000050	140.126	0.047	0.021
1.20	12.0068	120.068	1.201407	0.000080	0.000170	0.000050	120.123	0.055	0.017
1.00	10.0056	100.056	1.001330	0.000040	0.000140	0.000050	100.118	0.062	0.014
0.80	8.0045	80.045	0.801160	0.000020	0.000100	0.000050	80.104	0.059	0.011
0.60	6.0033	60.033	0.600943	0.000030	0.000050	0.000050	60.085	0.052	0.009
0.40	4.0022	40.022	0.400647	0.000040	0.000030	0.000050	40.059	0.037	0.007
0.20	2.0010	20.010	0.200303	0.000070	0.000060	0.000050	20.027	0.017	0.008
0.00	0.0000	0.000	-0.000010	0.000050	0.000040	0.000050	-0.001	-0.001	0.006
Modelled pressure: $p_{ind,mod} = I_{ind}/S_0$ with $1/S_0$ = 1/0.01000151 bar/(mV/V) = 99.9849 bar/(mV/V)									

Applied pressure	Mean indication	Variability intervals of corresponding series		Hysteresis	Modelled indicated pressure	Deviation	Expanded uncertainty of measurement	Error span	Error span from E2b[9]
p_{ref}	$I_{ind,mean}$	b'_{mean}	b_{mean}	h	$p_{ind,mod,mean}$	Δp_{mean}	$U(\Delta p_{mean})$	$U'(\Delta p_{mean})$	$U'(\Delta p_{mean})$
bar	mV/V	mV/V	mV/V	mV/V	bar	bar	bar	bar	bar
0.000	-0.000005	0.000050	0.000040	0.000023	0.000	0.000	0.007	0.007	n/a
20.010	0.200233	0.000100	0.000120	0.000140	20.020	0.010	0.013	0.024	0.024
40.022	0.400475	0.000060	0.000070	0.000343	40.041	0.019	0.022	0.041	0.041
60.033	0.600703	0.000080	0.000080	0.000480	60.061	0.028	0.030	0.058	0.058
80.045	0.800875	0.000090	0.000100	0.000570	80.075	0.030	0.035	0.066	0.065
100.056	1.001015	0.000090	0.000140	0.000630	100.086	0.030	0.039	0.070	0.070
120.068	1.201097	0.000080	0.000170	0.000620	120.092	0.024	0.040	0.063	0.064
140.079	1.401167	0.000090	0.000250	0.000607	140.096	0.017	0.041	0.058	0.058
160.091	1.601158	0.000090	0.000310	0.000557	160.092	0.001	0.041	0.041	0.042
180.102	1.801110	0.000130	0.000370	0.000407	180.084	-0.018	0.038	0.056	0.057
200.113	2.000923	0.000140	0.000270	0.000160	200.062	-0.051	0.029	0.080	0.075

Table E2a.2: Uncertainty budget at calibration pressure 100 bar

Quantity	Estimate	Variability interval	Probability distribution	Divisor	Standard uncertainty	Sensitivity coefficient	Contribution to uncertainty	Variance
X_i	x_i	$2a$	$P(x_i)$		$u(x_i)$	c_i	$u_i(y)$	$u_i^2(y)$
p_{ref}	100.056 bar	0.020 bar	normal	2	0.005 bar	-1	0.0050 bar	$2.50\cdot10^{-5}$ bar^2
$I_{ind,mean}$	1.001015 mV/V	0.000100 mV/V	normal	2	0.000025 mV/V	99.9849 bar/(mV/V)	0.0025 bar	$6.25\cdot10^{-6}$ bar^2
δI_{zero}	0.000000 mV/V	0.000030 mV/V	rectangular	$\sqrt{3}$	0.000009 mV/V	99.9849 bar/(mV/V)	0.0009 bar	$7.50\cdot10^{-7}$ bar^2
$\delta I_{repeat,mean}$	0.000000 mV/V	0.000090 mV/V	rectangular	$\sqrt{3}$	0.000026 mV/V	99.9849 bar/(mV/V)	0.0026 bar	$6.75\cdot10^{-6}$ bar^2
$\delta I_{reprod,mean}$	0.000000 mV/V	0.000140 mV/V	rectangular	$\sqrt{3}$	0.000040 mV/V	99.9849 bar/(mV/V)	0.0040 bar	$1.63\cdot10^{-5}$ bar^2
$\delta I_{hysteresis}$	0.000000 mV/V	0.000630 mV/V	rectangular	$\sqrt{3}$	0.000182 mV/V	99.9849 bar/(mV/V)	0.0182 bar	$3.31\cdot10^{-4}$ bar^2
Δp_{mean}	0.030 bar						0.0196 bar	$3.86\cdot10^{-4}$ bar^2
Δp_{mean} = 0.030 bar		**$U(\Delta p_{mean}) = k \cdot u(\Delta p_{mean})$ (k = 2)**				**$U(\Delta p_{mean})$ = 0.039 bar**		

[9] See Table E2b.1 for comparison with the other way of estimating the error span.

7.2.2 Example 2b – Determination of the transmission coefficient

Table E2b.1 Evaluation

Applied pressure	Relative expanded uncertainty	Mean output signal	Zero error	Repeatability	Reproducibility	Hysteresis
p_{ref}	$W(I_{ind,mean})$	$I_{ind,mean}$	$f_{0,rel.}$	$b'_{mean,rel.}$	$b_{mean,rel.}$	$h_{rel.}$
bar		mV/V				
0.000	n/a	-0.000005	n/a	n/a	n/a	n/a
20.010	$2.50 \cdot 10^{-4}$	0.200233	$1.5 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$	$7.0 \cdot 10^{-4}$
40.022	$1.25 \cdot 10^{-4}$	0.400475	$7.5 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$8.6 \cdot 10^{-4}$
60.033	$0.83 \cdot 10^{-4}$	0.600703	$5.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$	$8.0 \cdot 10^{-4}$
80.045	$0.63 \cdot 10^{-4}$	0.800875	$3.7 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$
100.056	$0.50 \cdot 10^{-4}$	1.001015	$3.0 \cdot 10^{-5}$	$9.0 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$
120.068	$0.42 \cdot 10^{-4}$	1.201097	$2.5 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$	$5.2 \cdot 10^{-4}$
140.079	$0.36 \cdot 10^{-4}$	1.401167	$2.1 \cdot 10^{-5}$	$9.3 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$4.3 \cdot 10^{-4}$
160.091	$0.32 \cdot 10^{-4}$	1.601158	$1.9 \cdot 10^{-5}$	$8.7 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$	$3.5 \cdot 10^{-4}$
180.102	$0.28 \cdot 10^{-4}$	1.801110	$1.7 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$	$2.1 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$
200.113	$0.25 \cdot 10^{-4}$	2.000923	$1.5 \cdot 10^{-5}$	$4.5 \cdot 10^{-5}$	$7.0 \cdot 10^{-5}$	$8.0 \cdot 10^{-5}$

Table E2b.2 Results

Applied pressure	Transmission coefficient	Deviation	Relative expanded uncertainty of measurement	Expanded uncertainty of measurement	Error span
p_{ref}	S_{mean}	ΔS_{mean}	$W(S_{mean})$	$U(S_{mean})$	$U'(S_{mean})$
	$I_{ind,mean}/p_{ref}$	$S_{mean} - S_0$	$2\sqrt{\sum w_i^2(S_{mean})}$	$W(S_{mean}) \cdot S_{mean}$	$U(S_{mean}) + \lvert\Delta S_{mean}\rvert$
bar	(mV/V)/bar	(mV/V)/bar		(mV/V)/bar	(mV/V)/bar
0.000	n/a	n/a	n/a	n/a	n/a
20.010	0.01000666	0.00000515	$6.7 \cdot 10^{-4}$	0.00000668	0.00001183
40.022	0.01000637	0.00000486	$5.4 \cdot 10^{-4}$	0.00000539	0.00001025
60.033	0.01000622	0.00000471	$4.9 \cdot 10^{-4}$	0.00000493	0.00000964
80.045	0.01000531	0.00000380	$4.4 \cdot 10^{-4}$	0.00000438	0.00000818
100.056	0.01000455	0.00000304	$3.9 \cdot 10^{-4}$	0.00000394	0.00000698
120.068	0.01000347	0.00000196	$3.3 \cdot 10^{-4}$	0.00000335	0.00000531
140.079	0.01000269	0.00000118	$3.0 \cdot 10^{-4}$	0.00000297	0.00000415
160.091	0.01000155	0.00000004	$2.6 \cdot 10^{-4}$	0.00000259	0.00000263
180.102	0.01000050	-0.00000101	$2.1 \cdot 10^{-4}$	0.00000215	0.00000316
200.113	0.00999897	-0.00000254	$1.2 \cdot 10^{-4}$	0.00000123	0.00000377
	Single value S_0:	0.01000151 (mV/V)/bar			

Table E2b.2 Uncertainty budget at the calibration pressure *p* = 100 bar

Quantity	Estimate	Variability interval	Probability distribution	Divi-sor	Relative standard uncertainty	Exponent associated with X_i	Contribution to uncertainty	Variance
X_i	x_i	$2a$	$P(x_i)$		$w(x_i)$	$c_i x_i y_i^{-1}$	$w_i(y)$	$w_i^2(y)$
p_{ref}	100.056 bar	0.020 bar	normal	2	$5.00\cdot10^{-5}$	-1	$5.00\cdot10^{-5}$	$2.50\cdot10^{-9}$
$I_{ind,mean}$	1.001015 mV/V	0.00010 mV/V	normal	2	$2.50\cdot10^{-5}$	1	$2.50\cdot10^{-5}$	$6.25\cdot10^{-10}$
K_{zero}	1	$3.0\cdot10^{-5}$	rectangular	$\sqrt{3}$	$8.66\cdot10^{-6}$	1	$8.66\cdot10^{-6}$	$7.50\cdot10^{-11}$
$K_{repeat,mean}$	1	$9.0\cdot10^{-5}$	rectangular	$\sqrt{3}$	$2.60\cdot10^{-5}$	1	$2.60\cdot10^{-5}$	$6.76\cdot10^{-10}$
$K_{reprod,mean}$	1	$1.5\cdot10^{-4}$	rectangular	$\sqrt{3}$	$4.33\cdot10^{-5}$	1	$4.33\cdot10^{-5}$	$1.87\cdot10^{-9}$
$K_{hysteresis}$	1	$6.3\cdot10^{-4}$	rectangular	$\sqrt{3}$	$1.82\cdot10^{-4}$	1	$1.82\cdot10^{-4}$	$3.31\cdot10^{-8}$
S_{mean}	0.01000455 (mV/V)/bar						$1.97\cdot10^{-4}$	$3.88\cdot10^{-8}$
S_{mean} = 0.0100045 (mV/V)/bar[10]	$W(S_{mean}) = k \cdot w(S_{mean})$ **(*k* = 2)**						**$W(S_{mean})$ = 3.9·10^{-4}**	

At the calibration pressure p_{ref} = 100 bar the expanded uncertainty $U(S_{mean})\big|_{100\text{ bar}}$ of the value $S_{mean}\big|_{100\text{ bar}}$ of the transmission factor is calculated as

$$U(S_{mean})\big|_{100\text{ bar}} = \left[W(S_{mean})\cdot S_{mean}\right]_{100\text{ bar}} = 3.9\cdot10^{-4}\cdot0.0100045\ \text{(mV/V)/bar}$$
$$= 3.9\cdot10^{-6}\ \text{(mV/V)/bar.}$$

Statement of a single value of the transmission coefficient

The general use of a pressure transducer does not imply the application of different transmission coefficients for the individual load steps (i.e. calibration pressures) but of only a single transmission coefficient for the total range covered by the calibration. This is preferably *the slope of the straight line fitted through all measured values of the output signal*.

When this characteristic quantity of the pressure transducer is used, a statement of compliance replaces the uncertainties associated with the individual values measured for the transmission coefficient.

This requires that the limits of permissible error be fixed, which can be done on the basis of the calibration results by the calculation of the error spans, i.e. by adding:

- the uncertainties associated with the individual values measured for the transmission coefficient, and
- the deviations of these values from the single value stated for the transmission coefficient.

Normally, error span values decrease with increasing pressure (see Figure 9). Two methods for fixing the limits of permissible error are possible:

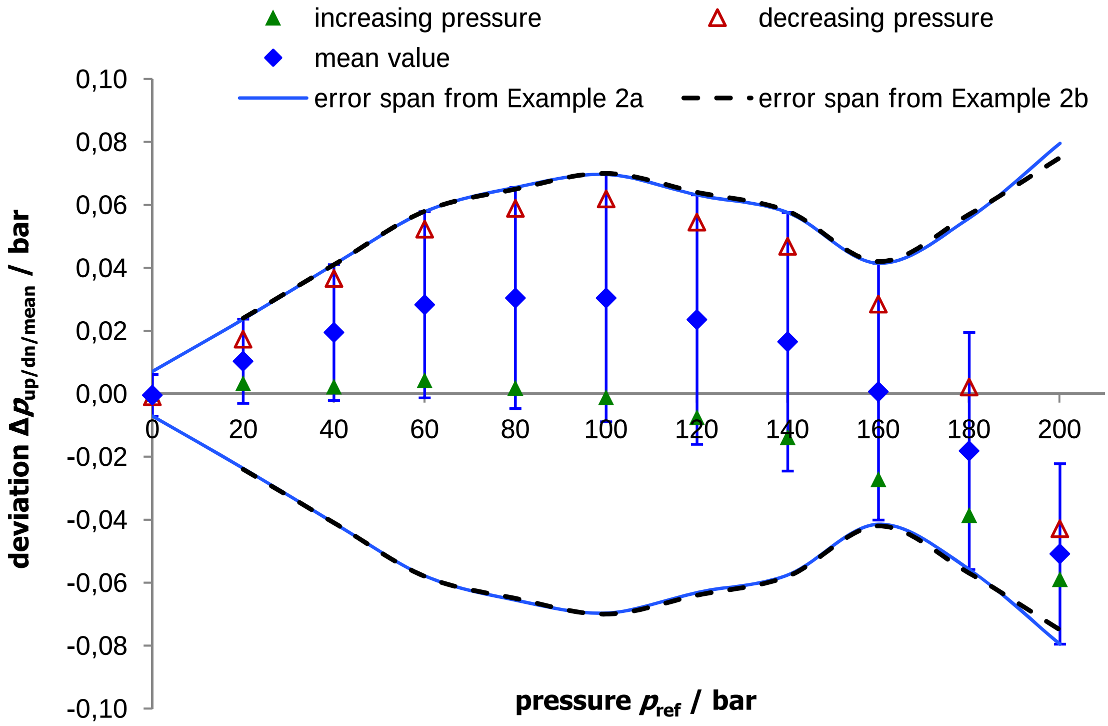
- one may choose the largest calculated error span as the limiting value, or

[10] The transmission coefficient is valid for the calibration pressure p_{ref} = 100.056 bar. It differs from the single transmission coefficient calculated from all calibration pressures.

- limiting values of the errors are described by suitable curves, e.g. polynomials.

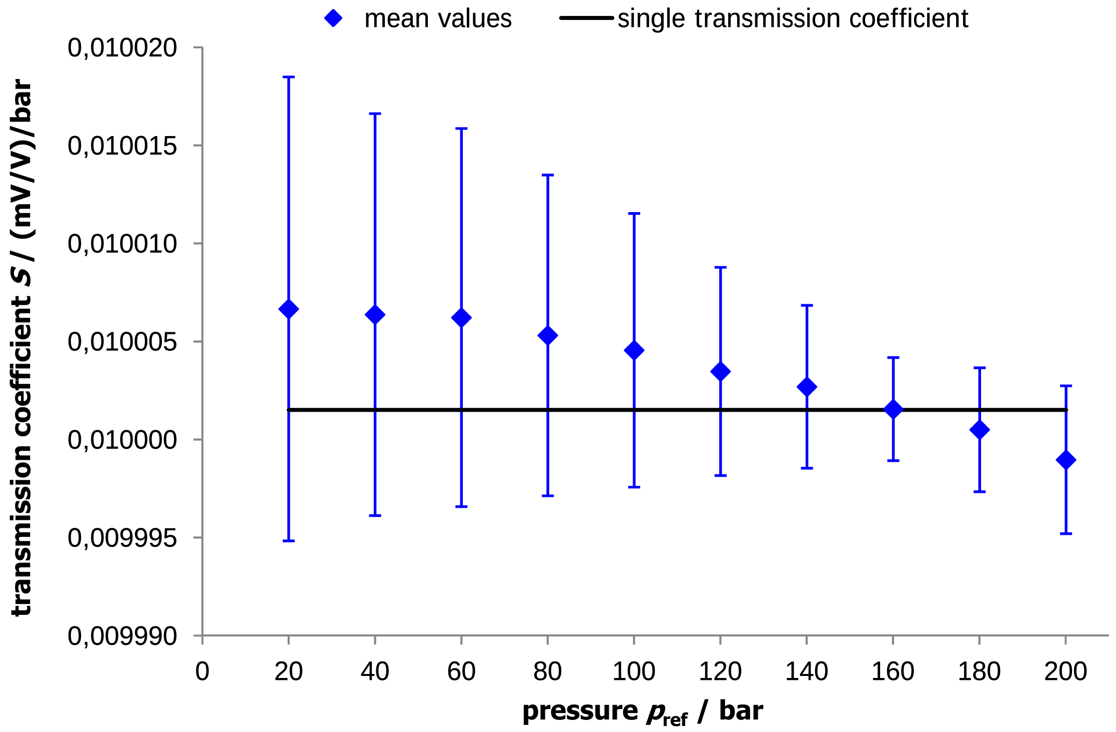
Note: The use of pressure-dependent limiting values of the errors is not common practice. However, it allows smaller uncertainties to be stated when pressure measurements are carried out with the calibrated instrument in the upper part of the measuring range.

In the case of objects to be calibrated whose transmission coefficient has been specified by the manufacturer, the limits of permissible error may alternatively be identified with the tolerance assigned to the specified value. In this case it must, however, always be checked whether the values of the transmission coefficient determined upon calibration, including their associated uncertainties and their systematic deviations from the specified single value, do not exceed the limits of permissible error.



The error bars indicate the expanded uncertainties of the mean values whereas the blue solid lines indicate the error spans $U'(\Delta p_{mean})$ as obtained in Example 2a. For comparison, the corresponding error spans obtained from the evaluation method of Example 2b are shown as black dashed lines. Ideally, the solid and dashed lines should coincide. Differences reflect the different ways of evaluation, including an interpolation step by modelling the output signal using a single transmission coefficient for Example 2a. Obviously, the overall result does not depend very much on such differences as was demonstrated. In Example 2a, the single transmission coefficient was chosen as S_0 = 0.01000151 (mV/V)/bar.

Figure 8 – Calibration of a pressure transducer



The solid line indicates the value of the single transmission coefficient. The error bars indicate the error spans corresponding to transmission coefficients obtained in Example 2b.

Figure 9 - Measured values and error spans of the transmission coefficient

EURAMET e.V.
Bundesallee 100
38116 Braunschweig
Germany

Phone: +49 531 592 1960
Fax: +49 531 592 1969
E-mail: secretariat@euramet.org