European
co-operation for
Accreditation

Publication Reference **EAL-G22**

Uncertainty of Calibration Results in Force Measurements

PURPOSE

This document has been produced to improve the harmonization in determination of uncertainties in force measurements. It provides information on measurement capabilities achieved by force calibration machines and gives guidance to calibration laboratories to establish a procedure for the expression of the overall uncertainty of calibration results of force transducers for calibrations performed according to EN 10002-3.

Authorship

This document has been revised by EAL Committee 2 (Calibration and Testing Activities), based on the draft produced by the EAL Expert Group on Mechanical Measurements.

Official language

The text may be translated into other languages as required. The English language version remains the definitive version.

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Guidance Publications

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Contents

Section **Page**

1 Introduction

1.1 The uncertainty of measurement associated with the force scales realized at national institutes of metrology is derived from the SI base units and ensured by means of several intercomparisons carried out worldwide in the past two decades. The relative uncertainty of measurement with which values of force can be realized by deadweight force standard machines is stated by various national laboratories as to be $\leq 2 \times 10^{-5}$. In practice, however, when deadweight standard machines are used to calibrate force transducers, the differences between the results obtained with different standard machines will generally be significantly greater due to the interaction effect. This became evident also in the past BCR and WECC interlaboratory comparisons based on force transducer calibrations that were carried out in 1987 and 1991, respectively [ref. 1, 2].

1.2 However, the measurement results achieved with force calibration machines (also deadweight machines) that are installed in accredited calibration laboratories must be traceable to the units realized with the national standard machines. In addition, to establish mutual confidence between the different calibration services, the differences of the calibration results of a force measuring device must be within the limits of the accredited best measurement capability of the laboratories concerned.

1.3 One of the recognised methods for investigating the parasitic effects of force introduction and irregularities of the calibration machines and for taking them into account is the method of interlaboratory comparison using precision force transducers as transfer standards in a limited range. The best measurement capability will thus be determined. By this technique, the advantages of high resolution and short-term repeatability of the force transducers will be exploited, whereas other systematic effects, such as those due to hysteresis, angular position, long term drift and creep effect will be considered in such a way that this will not influence the intercomparison results.

1.4 For commercial force transducers to be calibrated in force calibration machines, the calibration and classification procedure applied in Europe is that given in the European Standard EN 10002-3 [ref. 3]. Accordingly, in order to determine the uncertainty of measurement of the calibration results for a particular class of the device, the different contributions to the uncertainty must also be established.

2 Scope and field of application

2.1 The uncertainty requirements for the forces applied to calibrate force transducers are defined in several standards, e.g. EN 10002-3. However, the standards do not state a procedure for the determination of their uncertainty and the overall uncertainty of the calibration results. For the definition of the scope of accreditation of a calibration laboratory and for the evaluation of the uncertainty of calibration results, a guideline that ensures comparability of the calibration results and their uncertainties is necessary.

2.2 The scope of this guidance document is to provide a method to assess the best measurement capability achieved by the force calibration machines of accredited calibration laboratories and to describe a procedure for the expression of the overall uncertainty of calibration results of force transducers for calibrations performed according to EN 10002-3 at calibration laboratories.

2.3 The method developed allows the overall uncertainties in force measurements to be expressed, making also use of the instrument classification criteria established in the field of force measurement [ref. 4]. It is not the aim of this document to provide a method for the determination of the uncertainty of the force scales realized by force standard machines at national institutes of metrology, however, in many cases the method described may also be applicable here. This guideline is based on the method of estimation of uncertainty described in document EAL-R2 and in *Guide to the Expression of Uncertainty in Measurement* [ref. 5, 6]. Its concept may be applicable also to other fields of mechanical measurements.

3 Types of force calibration machines and examples of typical best measurement capability

3.1 The expected best measurement capabilities achieved by force calibration machines depend on the type of force realization. Table 3.1 shows typical values. The uncertainty of measurement with which values of forces are realized by deadweight force calibration machines in calibration laboratories may be calculated in a way similar to that of a standard machine and may be smaller than 5×10^{-5}. But according to the up-to-date development of the force transfer standards, the effort and outlay for the traceability of a best measurement capability smaller than 5×10^{-5} may be too large or technically infeasible. In most cases the requirements of the calibration laboratory are satisfied if a best measurement capability of 1×10^{-4} can be achieved. This enables the calibration laboratory to calibrate force measuring devices of the highest class 00 according to EN 10002-3.

3.2 The values in Table 3.1 can be used as best measurement capabilities at accredited laboratories on the assumption that the calibration laboratory will disseminate the quantity of force with the best measurement capability obtained as the mean value of at least three calibrations, each carried out in different angular positions, equally distributed around the central axis of the force calibration machine. This method of measurement has to be used because force is a vectorial quantity. For this reason the difference between the rotation effects of the force standard machine and the force calibration machine will basically not be considered in the calculations of the best measurement capability. If the rotation effect of the force calibration machine is unreasonably large, the reason for this is to be examined as it may be due to a faulty alignment of the machine.

Table 3.1: Ranges of typical best measurement capabilities

Types of force calibration machines	Examples of typical best measurement capability (expanded relative uncertainty)
Deadweight force calibration machine	5×10^{-5} to 1×10^{-4}
Hydraulic amplification force calibration machine	1×10^{-4} to 5×10^{-4}
Lever amplification force calibration machine	1×10^{-4} to 5×10^{-4}
Comparator force calibration machine with one or three reference force transducers	5×10^{-4} to 5×10^{-3}

3.3 In hydraulic and lever amplification machines, the lower values for the best measurement capability can be achieved by the correction of the systematic component of the amplification effect. For the determination of the best measurement capability of the comparator type force calibration machine, it is desirable to first calibrate the machine’s incorporated reference force transducer in a force standard machine and finally carry out the calibration of the force calibration machine by means of the force transfer standards.

4 Measurement plan to determine the best measurement capability achieved by the force calibration machines

4.1 To get the relevant input quantities for the determination of the uncertainty according to the EAL-R2 the following measurement plan should be applied.

- Selection of several force transducers as transfer standards which cover the whole range of forces of the force calibration machine. The working ranges of the transfer standards should normally begin at 40 % or 50 % of the nominal force of the transfer standard. This would minimize the influence of the interaction effect. This in general requires the application of three to five transfer standards. Separate transfer standards for tension and compression may be needed.
- Calibration of these transfer standards in a national force standard machine to determine their reference values. (The measurement shall be carried out in *n* rotational positions (at least three) and shall include hysteresis measurements. The measurements are to be repeated once in at least one of the rotational positions.)
- Calibration of the force calibration machine under consideration by means of transfer standards. The measurement procedure will be similar to the calibration of the transfer standard.

- Determination of the relative deviations between the reference values and the results of the overall mean values of the calibration of the force calibration machine for each force step within the total measurement range.
- Recalibration of the transfer standards in the national force standard machine to check the calibration status.

5 Evaluation of the expanded uncertainty of measurement of the reference values

5.1 For the evaluation of the relative uncertainties of measurement EAL-R2 is applied in connection with the *Guide to the Expression of Uncertainty in Measurement* [ref. 6]. The standard relative uncertainty and the related expanded relative uncertainty associated with the reference values of the transfer standards will be calculated in three steps

- **Step 1:** Determination of the expanded relative uncertainty W_{fsm} for the realization of force by the force standard machine.

  The expanded relative uncertainty with which the unit of force is realized by a typical *national force standard machine* is e.g. $W_{\mathrm{fsm}} = 2 \times 10^{-5}$ for a deadweight machine [7]. For lever or hydraulic amplification machines, W_{fs} may be evaluated from basic principles or it may be determined experimentally by means of comparison measurements with deadweight machines. Typical values of the uncertainties of measurement are e.g. 1×10^{-4} to 2×10^{-4}.

- **Step 2:** Determination of the expanded relative uncertainty W_{tsd} of the calibration of the transfer standards in the force standard machine.

  The quantity determined in the calibration of a force transducer used as *transfer standard* for the selected force steps is its calibration coefficient K_{tsd} which is the ratio of the value of the force F_{fsm} applied to the value x indicated by the force transducer.

  $$K_{\mathrm{tsd}} = \frac{F_{\mathrm{fsm}}}{x} \qquad (1)$$

  To eliminate the influence of the rotation effect the indicated value x taken in the equation (1) is the mean value of n rotational positions of the transducer uniformly spaced around its axis.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

where x_{i} are the values indicated by the force transducer in the different rotational positions.

The relative variance of the mean indication is

$$w^2(\bar{x}) = \frac{u^2(\bar{x})}{\bar{x}^2} = \frac{1}{n}\frac{a_{\mathrm{rep}}^2}{3\,\bar{x}^2} \qquad (3)$$

with assumed equal variance of the indication in the different rotational positions. This variance is estimated by the half-width a_{rep} of the maximum possible variation of repeatability without rotation of the transducer (rectangular probability distribution).

For the application of the transfer standard the influence of the *drift* D has to be incorporated by a further relative uncertainty contribution as follows:

$$w^2(D) = \frac{a_{\mathrm{drift}}^2}{6} \qquad (4)$$

where its value is estimated by a triangular probability distribution of half-width a_{drift} of relative variation of sensitivity. This assumption is justified if the comparison measurements are made during a short period of time (typically about one month).

Remark: If the drift is not time-dependent, the triangular distribution has to be replaced by the rectangular distribution.

The combined standard relative uncertainty of the value of force indicated by the transfer standard $w(K_{\mathrm{tsd}})$ and its expanded relative uncertainty W_{tsd} (coverage factor $k = 2$) can be determined by the following equations:

$$w(K_{\mathrm{tsd}}) = \sqrt{w^2(\bar{x}) + w^2(D)} \qquad (5)$$

$$W_{\mathrm{tsd}} = k \times w(K_{\mathrm{tsd}}) \qquad (6)$$

- **Step 3:** Calculation of the expanded relative uncertainty of the reference values $W_{\mathrm{refv.}}$

Finally, the expanded relative uncertainty of the *reference value* will be evaluated as follows:-

$$W_{\mathrm{refv}} = k \times \sqrt{w^2(F_{\mathrm{fsm}}) + w^2(K_{\mathrm{tsd}})} \qquad (7)$$

5.2 Table 5.2 shows typical examples of the expanded relative uncertainty of reference values of four different qualities of force transfer standards in relation to the different types of force standard machines. The transfer standards with the lowest relative uncertainty achievable to date, as shown in column 2, are the force transducers for the range between 100 kN and 500 kN. For the range below 2 kN (column 3), it is still very difficult to find transfer standards of low relative uncertainty. If the force standard machines are not deadweight machines, the uncertainties of the transfer standards are not very important as shown in columns 4 and 5. However, in the case of forces above 3 MN investigations have to be carried out to select the proper transfer standards.

Table 5.2: Examples of expanded relative uncertainty of reference values

Force standard machine

	Deadweight	**Deadweight ≤ 2 kN**	**Lever or hydr. ampl.**	**Lever or hydr. ampl.**
W_{fsm}	2 x 10^{-5}	2 x 10^{-5}	1 x 10^{-4}	2 x 10^{-4}

Examples of force transfer standards

a_{drift}	3 x 10^{-5}	5 x 10^{-5}	5 x 10^{-5}	1 x 10^{-4}
$w^2(D)$	1,5 x 10^{-10}	4,2 x 10^{-10}	4,2 x 10^{-10}	1,7 x 10^{-9}
a_{rep}	1 x 10^{-5}	1,5 x 10^{-5}	2,5 x 10^{-5}	5 x 10^{-5}
$w^2(x)$	1,1 x 10^{-11}	2,5 x 10^{-11}	7 x 10^{-11}	2,8 x 10^{-10}
W_{tsd}	2,5 x 10^{-5}	4,2 x 10^{-5}	4,4 x 10^{-5}	8,9 x 10^{-5}

Expanded relative uncertainty of reference values

W_{refv}	3,2 x 10^{-5}	4,7 x 10^{-5}	1,1 x 10^{-4}	2,2 x 10^{-4}

6 Calculation of the best measurement capability achieved by the force calibration machine

6.1 After the completion of the calibration of the force calibration machine, its best measurement capability in relative terms may be determined according to the following two further steps. The calculation is based on the assumption that the force transducer to be calibrated will not introduce further components of uncertainty.

- **Step 4:** Determination of expanded relative uncertainty W_{fcm} related to the realization of force by the force calibration machine.

The input estimates for the determination of the relative uncertainty W_{fcm} are defined in Table 6.1 and obtained by the direct comparison of the reference values with the indicated force values of the force calibration machine.

Table 6.1: Uncertainty contributions for the determination of the best measurement capability for the selected steps within a force range of the force calibration machine (*a*: relative half-width of the maximum deviation)

Uncertainty contribution	**Half-width *a***	**Probability distribution**	**Input estimate**
Relative deviation between reference values of force and values realized in the force calibration machine	$a_{\text{rel\_dev}}$	triangular distribution	Δ_D
Relative lack of *repeatability* of force calibration machine determined with unchanged position of the force transducer *Remark: uncertainty of force transducer has been considered here to be negligible*	$a_{\text{rep\_fcm}}$	rectangular distribution	Δ_R
Relative deviation of *hysteresis* between reference hysteresis of the transfer standard and hysteresis measured in the force calibration machine.	$a_{\text{hys\_fcm}}$	rectangular distribution	Δ_H

6.2 The corresponding relative variances are to be determined according to the following equations:

$$w^2(\Delta_D) = \frac{a^2_{\text{rel\_dev}}}{6} \qquad (8)$$

$$w^2(\Delta_R) = \frac{a^2_{\text{rep\_fcm}}}{3} \qquad (9)$$

$$w^2(\Delta_H) = \frac{a^2_{\text{hys\_fcm}}}{3} \qquad (10)$$

6.3 The combined standard relative uncertainty w_{fcm} and the expanded relative uncertainty W_{fcm} related to the realization of force by the force calibration machine are to be determined according to the following equations (11) and (12):

$$w_{fcm} = \sqrt{w^2(\Delta_{\mathrm{D}}) + w^2(\Delta_{\mathrm{R}}) + w^2(\Delta_{\mathrm{H}})} \qquad (11)$$

$$W_{\mathrm{fcm}} = k \times w_{\mathrm{fcm}} \qquad (12)$$

6.4 Table 6.4 shows four typical examples of the measurement results obtained by force calibration machines. The values indicated in column 2 for the deadweight machine are more common for machines with a capacity above 2 kN. The comparison measurements of the lower capacity machines will generally show relative deviations ($a_{\mathrm{rel\_dev}}$) as indicated in column 3. Unless the systematic variation of the multiplication ratio at increasing forces is compensated in a lever of hydraulic amplification machine, the relative deviation will presumably be between 1 x 10^{-4} and 5 x 10^{-4}. Column 4 shows the typical values of a lever or hydraulic amplification machine. The relative deviation of the comparator machine in colum 5 depends on the structure of the loading frame and control system of the machine. In addition, the components of the uncertainties of the incorporated reference force transducer used and its long-term instability must be considered as indicated in step 5.

- Step 5: Calculation of the best measurement capability W_{bmc}

  The *best measurement capability* achieved by the deadweight and lever of hydraulic amplification machines will be calculated by the following equation:

$$W_{\mathrm{bmc}} = k \times \sqrt{w_{\mathrm{refv}}^2 + w_{\mathrm{fcm}}^2} \qquad (13)$$

Table 6.4: Examples of relative expanded uncertainty obtained by force calibration machines

Examples of force calibration machine

	Deadweight I	**Deadweight II**	**Lever or hydr. ampl.**	**Comparator Machine**
$a_{\mathrm{rel\_dev}}$	5 x 10^{-5}	1 x 10^{-4}	2 x 10^{-4}	4 x 10^{-4}
$w^2(\Delta_{\mathrm{D}})$	4,2 x 10^{-10}	1,7 x 10^{-9}	6,7 x 10^{-9}	2,7 x 10^{-8}
$a_{\mathrm{rep\_fcm}}$	1 x 10^{-5}	1 x 10^{-5}	2,5 x 10^{-5}	5 x 10^{-5}
$w^2(\Delta_{\mathrm{R}})$	3,3 x 10^{-11}	3,3 x 10^{-11}	2,1 x 10^{-10}	8,3 x 10^{-10}
$a_{\mathrm{hys\_fcm}}$	5 x 10^{-6}	5 x 10^{-6}	2,5 x 10^{-5}	1 x 10^{-4}
$w^2(\Delta_{\mathrm{H}})$	8,3 x 10^{-12}	8,3 x 10^{-12}	2,1 x 10^{-10}	3,3 x 10^{-9}
W_{fcm}	4 x 10^{-5}	8 x 10^{-5}	1,8 x 10^{-4}	3,5 x 10^{-4}

6.5 In the calculation for machines of the comparator type, two additional uncertainty components, i.e. the uncertainty $W_{\mathrm{ref\_tra}}$ of the *reference force transducer* itself and the estimated *long-term instability* $W_{\mathrm{ref\_instb}}$ of the reference force transducer, must be considered and applied in the following equation:

$$W_{\mathrm{bcm}} = \sqrt{w_{\mathrm{refv}}^2 + w_{\mathrm{fcm}}^2 + w_{\mathrm{ref\_tra}}^2 + w_{\mathrm{ref\_instab}}^2} \qquad (14)$$

6.6 Table 6.6 finally shows the typical overall results of the best measurement capability for different types of force calibration machines. The relative uncertainty of the reference force transducer will be calculated according to the procedure of sections 7 to 9. The long-term instability of the reference force transducer is to be determined from previous calibrations or by estimations. This uncertainty component may be calculated by assuming a symmetrically triangular distribution of variation in sensitivity.

Table 6.6: Examples of the best measurement capability W_{bmc}

Force calibration machine

	Deadweight I	**Deadweight II**	**Lever or hydr. ampl.**	**Comparator machine**
$W_{\mathrm{ref\_tra}}$	–	–	–	3 x 10^{-4}
$W_{\mathrm{ref\_instab}}$	–	–	–	2 x 10^{-4}
W_{refv}	3,2 x 10^{-5}	4,7 x 10^{-5}	3,5 x 10^{-5}	3,5 x 10^{-5}
W_{fcm}	4,3 x 10^{-5}	8,3 x 10^{-5}	1,8 x 10^{-4}	3,5 x 10^{-4}
W_{bmc}	5,4 x 10^{-5}	9,5 x 10^{-5}	1,8 x 10^{-4}	5 x 10^{-4}

7 Uncertainty contributions derived from the calibration results and estimation of variances

7.1 Since the adoption of the new European Standard EN 10002-3 by the member countries in 1992, a uniform procedure for the calibration and classification of force transducers can be applied in Europe. The classification components of EN 10002-3 deliver the input for the evaluation of the standard uncertainty of the calibration results according to EAL-R2. The uncertainty contributions of force transducers are determined from repeated observations. They are considered uncorrelated input quantities. Table 7.1 shows the proposed probability distribution of these input quantities.

Table 7.1: Probability distributions assumed for the different input quantities (*a*: relative half-width of the maximum deviation of the input quantity)

Uncertainty contributions (input quantities)	Probability distribution	Estimated relative variance
zero deviation	rectangular distribution	$w_{\mathrm{zer}}^2 = a^2/3$
reproducibility without rotation	rectangular distribution	$w_{\mathrm{rep}}^2 = a^2/3$
reproducibility with rotation	U-shaped distribution	$w_{\mathrm{rot}}^2 = a^2/2$
interpolation deviation	triangular distribution	$w_{\mathrm{inp}}^2 = a^2/6$
resolution	rectangular distribution	$w_{\mathrm{res}}^2 = a^2/3$
reversibility (hysteresis)	rectangular distribution	$w_{\mathrm{rev}}^2 = a^2/3$

8 Calculation of uncertainties

8.1 After the relative variance for each force step has been determined, the relative combined standard uncertainty w and the relative expanded uncertainty W_{tra} for $k = 2$ will be calculated by the following equations (15) and (16) for each force step.

$$w_{\mathrm{tra}} = \sqrt{w_{\mathrm{zer}}^2 + w_{\mathrm{rep}}^2 + w_{\mathrm{rot}}^2 + w_{\mathrm{inp}}^2 + w_{\mathrm{res}}^2 + w_{\mathrm{rev}}^2} \tag{15}$$

$$W_{\mathrm{tra}} = k \times w_{\mathrm{tra}} \tag{16}$$

8.2 The relative expanded uncertainty of calibration W will be determined by considering the best measurement capability of the force calibration machine as follows:

$$W = k \times \sqrt{w_{\mathrm{tra}}^2 + w_{\mathrm{bmc}}^2} \tag{17}$$

9 Calculation of the relative uncertainty of calibration results according to EN 10002-3

9.1 The evaluation of the calibration results allows the force measuring devices to be put into four different classes according to EN 10002-3. Table 9.1a contains the maximum permissible errors for the classification in class 00. These values are used as input quantities to determine the relative variance according to the formulas of Table 7.1. The results of the maximum overall uncertainty applying equations (15) to (17) are shown for class 00 in Table 9.1b.

9.2 The relative uncertainty of the force transducer calibration is to be calculated after having obtained the calibration results for each force step. For a given class, the relative uncertainty will be determined from the highest calculated value of the uncertainty within the range of forces. In general, this relative uncertainty will refer to the lowest force of the range.

Table 9.1a: Maximum relative errors and corresponding variance

Error of calibration force W_{bmc} 0,01%

Uncertainty contributions (input quantity)	**max. error Class 00**	**rel. variance Class 00**
zero deviation	0,012 %	$1,2 \times 10^{-9}$
reproducibility without rotation	0,025 %	$5,2 \times 10^{-9}$
reproducibility with rotation	0,05 %	$3,1 \times 10^{-8}$
interpolation deviation	0,025 %	$2,6 \times 10^{-9}$
resolution	0,025 %	$5,2 \times 10^{-9}$
reversibility (hysteresis)	0,07 %	$4,1 \times 10^{-8}$

Table 9.1b: Maximum relative uncertainty for class 00

Combined rel. standard uncertainty w_{tra}	0,029 %
Expanded rel. uncertainty W_{tra}	0,059 %
Max. rel. uncertainty of calibration W	0,06 %

9.3 Table 9.2 shows in the last column the maximum possible relative uncertainty for all of the four classes of EN 10002-3. It has been calculated using maximum permissible errors according to the standard as input quantities to the equations (15) to (17). In the middle column, the minimum values of each class are given. They are identical with the maximum values of the respective higher class. However, for class 00 the minimum uncertainty cannot be lower than the best measurement capability of the force calibration machine. The uncertainty of the calibration results will be calculated according to equation (17). If this value is smaller than the minimum value for the class given in Table 9.2, the value from the table is to be used. All other quantities influencing the measurement result in practice, e.g. long-term instability and temperature influence, need to be additionally taken into account by the user of the calibrated device.

Table 9.2: Limits for the expanded relative uncertainty for different classes of EN 10002-3

	min.	**max.**
Class 00	W_{bmc}	0,06 %
Class 0.5	0,06 %	0,12 %
Class 1	0,12 %	0,24 %
Class 2	0,20 %	0,45 %

10 Block diagram

10.1 Fig. 1 shows the block diagram of the uncertainty chain developed in this guidance document. The uncertainties are defined at four different levels. To define the scope of accreditation of a laboratory, the required input quantities are added at two different levels. For the expression of the uncertainty of the calibration results of the force transducer, the respective input quantities are combined with the uncertainty of the laboratory.

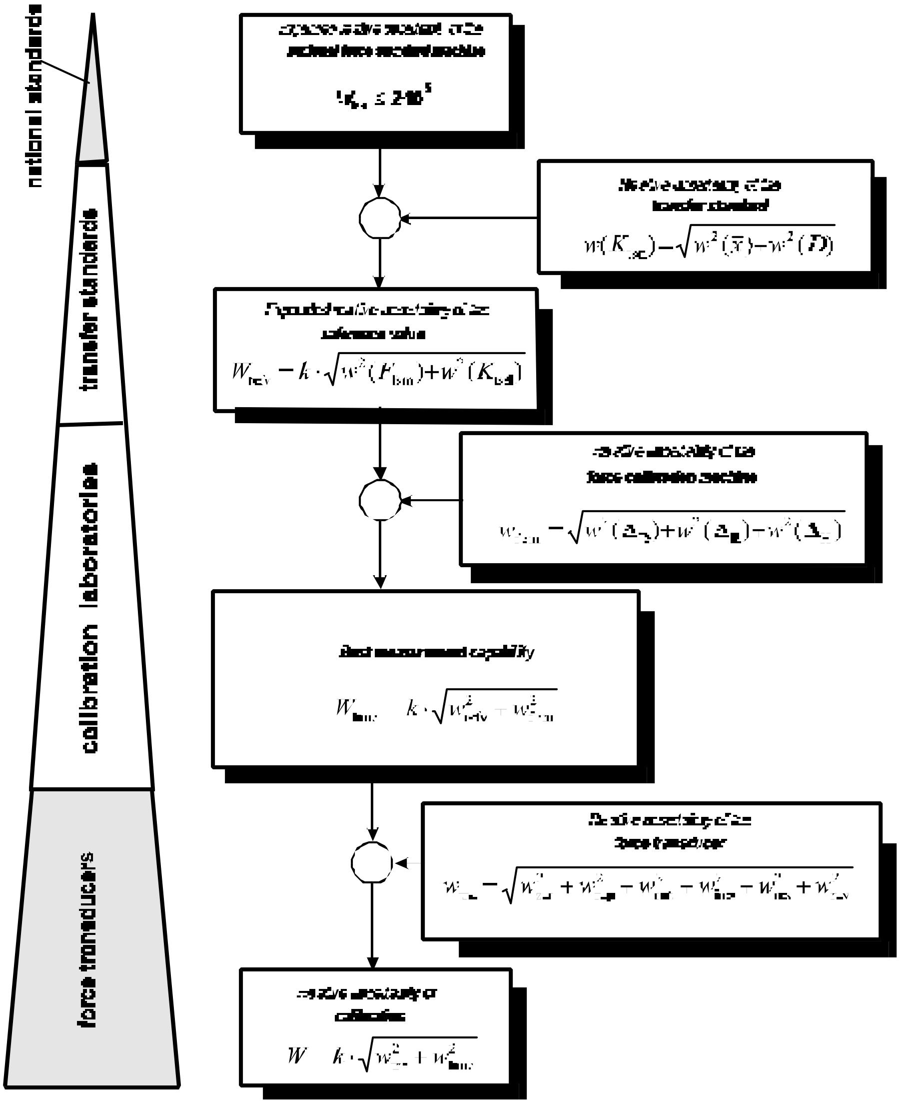

Fig. 1. The hierarchy of force calibration and its consequences for the uncertainty at the different levels

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