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Traceability of thread measurements

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Deutscher Kalibrierdienst (DKD) – German Calibration Service

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.
This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.
The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD expert reports aim to provide background information and references in connection with other DKD documents as, for example, the DKD guidelines. In some cases, they may even go far beyond these documents. They do not replace the original DKD documents but do provide a lot of supplementary information worth knowing. The expert reports do not necessarily reflect the views of the DKD's Management Board or Technical Committees in all details.

DKD expert reports are intended to present significant aspects from the field of calibration. Through publication by the DKD they are made available to the large community of calibration laboratories, both nationally and internationally.

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1 Introduction

Metrology plays an essential role in the quality assurance of thread production. While the testing of workpiece threads is typically carried out by means of gauges, the plug and ring gauges used must be previously calibrated, using suitable measuring methods. In Germany, the calibration of thread gauges is currently carried out by 47 calibration laboratories accredited for thread measurement by the German Accreditation Body (Deutsche Akkreditierungsstelle or DAkkS for short). By means of reference standards, these laboratories establish the traceability of their measurements to national standards of the Physikalisch-Technische Bundesanstalt (PTB) or other National Metrology Institutes (NMI), which are directly linked to the metre, the unit of length in the International System of Units (SI), via primary measurement procedures. The principle of this unbroken chain of comparison measurements – each with a known measurement uncertainty – is called traceability and is a central component of the quality infrastructure (Figure 1).

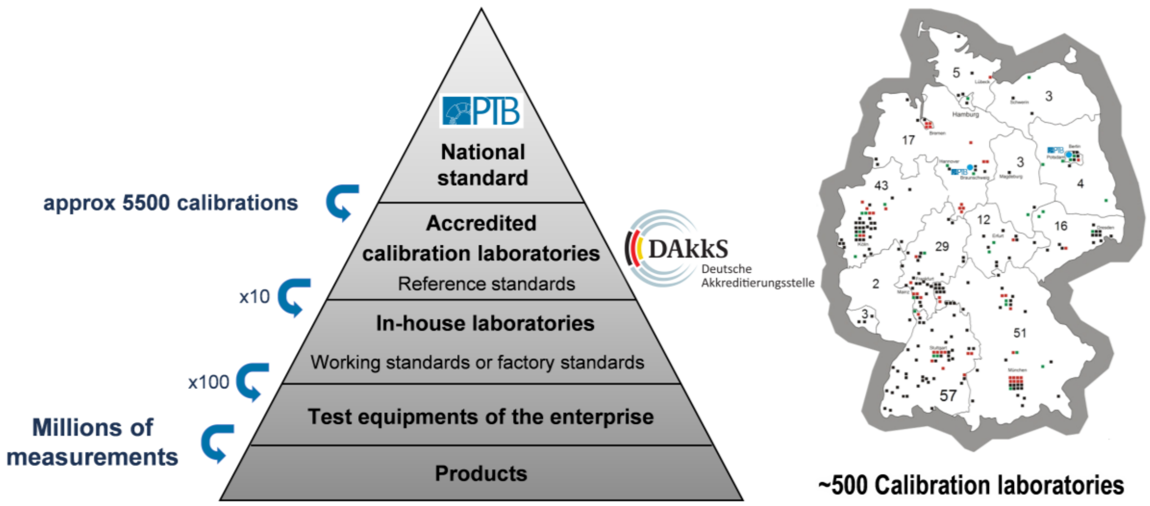

Figure 1: The calibration pyramid particularly illustrates the interaction between DAkkS and PTB as part of the national quality infrastructure

Over the past decades, the ever-growing demand from industry for a more precise measuring technology to increase the quality of production with ever smaller manufacturing tolerances has led to the development of innovative measuring methods in thread measurement. Established methods such as the three-wire or two-ball method are now frequently supplemented by profile methods (stylus instrument procedures) and coordinate measurements. And there are other approaches using optical or other kinds of non-contact sensors. The variety of available measuring methods requires harmonisation because it must be ensured that different methods provide comparable measuring results. The difficulties already start with the definition of the fundamental quantities (thread parameters). These parameters must be unambiguous and accessible for all measurement methods [1].
The basic metrological principles and test instructions for cylindrical threaded plug gauges and rings are described in the guidelines VDI/VDE/DGQ 2618 Part 4.8 and 4.9:2006-04 [2][3]. A detailed description of the procedure for determining the pitch diameter with the three-wire or two-ball method according to Berndt [4] and Kochsiek and Lerch [5] can be found in the European guideline EURAMET cg-10:2012-12 [6]. The application of these guidelines is limited explicitly to cylindrical threads. Besides, these guidelines rather focus on the technical details of measuring and calculating the determining parameters and not so much on providing basic statements on how to realise a reliable and task-specific traceability.

ISO/IEC 17025 is the globally valid standard for the accreditation of testing and calibration laboratories. It specifies the general requirements for quality assurance. Since 1 July 2021, the German edition of the revised version of DIN EN ISO/IEC 17025:2018-03 is binding for DAkkS accreditations. To ensure the validity of measurement results, the standard requires – particularly in section 7.7.2 – participation in comparison measurements with other laboratories [7].

The last comprehensive interlaboratory comparison for thread measurement was organised by the Technical Committee *Length* of the German Calibration Service (DKD). It took place between June 2016 and March 2017 with 20 participating laboratories. The comparison report was published in December 2017. It documents the measurement results obtained from measurements on two metric thread plug gauges and two metric thread ring gauges [8]. From a total of 711 individual results, 110 results were not satisfactory pursuant to DIN EN ISO/IEC 17043:2010-05 and thus caused a "notification for action" [9]. And it is also the result of this interlaboratory comparison that has prompted a thorough examination of the topic of traceability in thread calibration.

This expert report is intended to provide an in-depth overview of the requirements necessary for reliable and traceable thread measurements to ensure comparability both between different laboratories and when using different measuring methods. As a first step, the scope of application is defined, and the most important thread parameters are summarised. Chapter 4 gives an overview of the measurement methods currently used in calibration. Chapter 5 describes the influences of the measurement uncertainty depending on the method used and discusses various methods for determining these influences. The topic of traceability and the associated requirements for measuring instruments and equipment are discussed in chapter 6. Finally, chapter 7 lists specific recommendations for practical application in calibration laboratories, as part of a catalogue of measures to be taken.

2 Scope of application

This report is applicable to single and multiple-threaded cylindrical or tapered plug gauges and ring gauges, with straight flanks and positive flank angles.

3 Thread parameters

We know from experience that there are often misunderstandings when dealing with the determination of some of the parameters. For example, the meaning of the different concepts of pitch diameter is difficult to understand. And frequently the terms "lead" and "pitch" are used imprecisely. Yet a solid understanding of these quantities is one of the most important prerequisites for a reliable thread calibration. The essential terms for thread calibration are listed in Table 1 and explained in Figure 2, using the example of a single-start external thread.

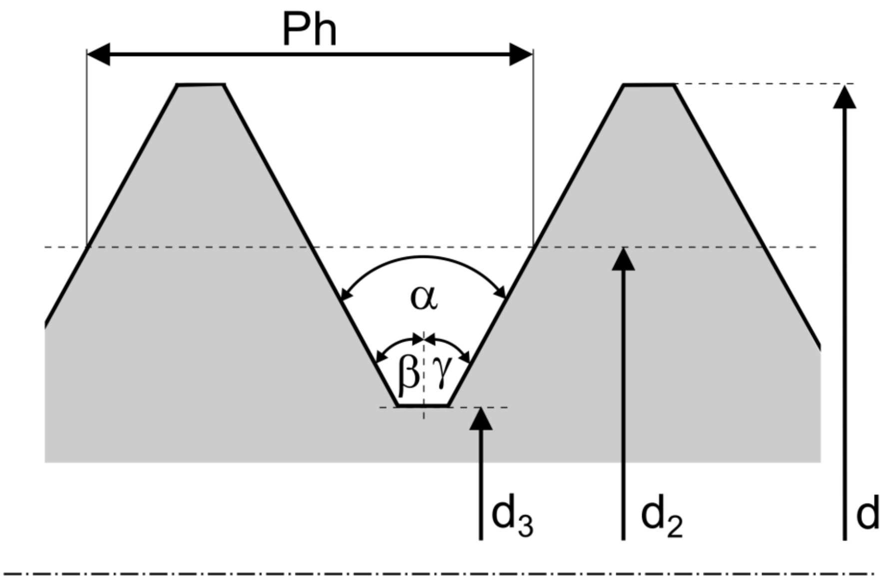

Figure 2: Parameters on a single-start external thread according to DIN 2244:2002-05

Table 1: Thread parameters according to DIN 2244:2002-05

Parameter	**Symbol** External thread / Internal thread
Pitch diameter	d_2 / D_2
Simple pitch diameter	d_{2s} / D_{2s}
Virtual pitch diameter	d_{2P} / D_{2P}
Major diameter	d / D_4
Minor diameter	d_3 / D_1
Pitch	P
Lead	Ph
Thread angle	α
Flank angle	β, γ

The terms and parameters for cylindrical threads with profiles derived from triangles are listed in DIN 2244:2002-05 [10]. At the international level, ISO 5408:2009-06 [11] constitutes the counterpart. Here, terms for cylindrical and tapered threads with symmetrical and asymmetrical profiles are defined. In Germany, however, DIN 2244:2002-05 is given priority although tapered threads are not considered. The symbols from Table 1 largely correspond to those used in the ISO standard – the only difference is that the ISO standard uses β_1 and β_2 to designate the flank angles. Their significance as well as the differences between the standards are explained below.

The last revision of DIN 2244 took place in 2002 replacing the 1977 version. Thread adjustments, tolerances and deviations were added. Some basic terms were added, and symbols were changed, some terms were brought in line with ISO 5408:1983. A significant change consisted in dividing the thread axis into the axis of the simple pitch diameter, the axis of the pitch diameter and the axis of the helix, each with their own definitions. This allows a more precise description of the quantities to be calibrated, but it also entails a plenitude of terms which makes understanding more difficult. The reason behind this was the realisation that the original thread axis was insufficiently defined for real threads [10].

Besides the above-mentioned standards, the European calibration guideline EURAMET cg-10 plays a decisive role for the nomenclature in thread metrology [6]. The five different calibration options formulated there for the first time have been integrated into national guidelines such as [2] and [3]; today they form the essential basis for the work of calibration laboratories. These calibration options are intended to establish a metrological relationship to the geometrically defined parameters, in particular the different concepts of the pitch diameter. However, conformity of the quantities – which results from the definition of the measurement or evaluation conditions in EURAMET cg-10 – with the purely geometrically defined parameters from DIN 2244 or ISO 5408 is questionable, at least in some cases. This is made clear by the fact that EURAMET cg-10 defines five options for the evaluation of only three parameters. Consequently, DAkkS-accredited calibration laboratories and NMIs explicitly state the option used according to EURAMET cg-10 or [2] or [3], given that the mere reference to geometrically defined parameters does not guarantee comparability [12].

To illustrate the difficulties, the three pitch diameter concepts defined in DIN 2244 and ISO 5408 are briefly compared.

- According to DIN 2244, the **simple pitch diameter** $d_{2\mathrm{s}}$ / $D_{2\mathrm{s}}$ is the diameter of the geometrically ideal circular cylinder whose surface lines intersect the thread in such a way that the sections in the thread gaps are equal to half the pitch.
- According to DIN 2244, the **pitch diameter** d_2 / D_2 is the diameter of a geometrically ideal circular cylinder whose surface lines intersect the thread in such a way that the sections of the surface line formed by a thread gap and an adjacent thread tooth of the same thread are of equal length.
- According to DIN 2244, the **virtual pitch diameter** $d_{2\mathrm{P}}$ / $D_{2\mathrm{P}}$ is the pitch diameter of a geometrically ideal thread which can just be screwed together with the workpiece thread without play around the thread flanks over a defined screw-in length.

For geometrically ideal threads, all three terms coincide. For real threads, however, there are generally three different values.

In the case of a simple pitch diameter, only the gap is measured, and its width is compared with the nominal value of the pitch[1]. EURAMET cg-10 additionally distinguishes whether the nominal value (option 1a) or the measured value (from an additional measurement) is used for the thread profile angle (option 1b).

Instead, the pitch diameter considers the actual value of the pitch, which consequently has to be determined from an additional measurement. Again, EURAMET cg-10 distinguishes whether the nominal value (option 2a) or the measured value (from an additional measurement) is used for the thread profile angle (option 2b).

In terms of definition, the virtual pitch diameter clearly stands out from the other two parameters. Instead of considering certain distances in the respective axial section of the

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[1] DIN 2244 uses the term division. What is actually meant is the nominal pitch, i.e., its nominal value. Otherwise, the simple pitch diameter and the pitch diameter would always be identical. See also [1].

thread, the mating ability with an ideal-geometric mating thread is formulated here as a condition. On the one hand, this turns the virtual pitch diameter into a real significant quantity, given that its specification alone is sufficient to describe the mating ability with another thread. On the other hand, and from a metrological point of view, the virtual pitch diameter proves to be the most challenging thread parameter. A determination according to definition (in the sense of DIN 2244 or ISO 5408) requires a surface measurement of the entire thread flanks as well as a mathematically complex determination of the corresponding minimum circumscribe and maximum inscribe thread.

To determine the virtual pitch diameter "defined" according to EURAMET cg-10, both partial flank angles must be measured in addition to the quantities given in option 2b to take into account a possible asymmetry of the thread profile. Furthermore, two correction amounts must be added to account for the deviations in pitch and angle from their nominal values. There's only an approximate correspondence of the thus determined quantity with the virtual pitch diameter defined in DIN 2244 or ISO 5408. However, the advantage of the definition by EURAMET cg-10 consists in offering the possibility of a comparatively simple metrological determination and in creating a basis for the comparability of measurement results.

In addition to the various concepts of pitch diameter, the different terms used for lead Ph and pitch P on the thread are to be considered here in a metrological context. Unfortunately, these two terms are often mixed up. This is also due to some sort of imprecision in the terminology used or, at least, some didactically questionable remarks in the standards concerning the determining quantities. For example, in a footnote to definition 3.3.18 *Lead Ph,* DIN 2244 explicitly allows the symbol P to be used for lead instead of Ph. However, lead and pitch describe completely different characteristics of the thread. The lead is an individual characteristic of each individual flank of the thread, while the term pitch describes the position of two adjacent flanks to each other. Since the terms seem to overlap for single-start threads, that is to say they are used interchangeably, specifying the pitch only makes sense for multi-start threads.

Figure 3 shows a three-start external thread. Here, the difference between the two parameters is obvious. Currently, the designations Ph_i und $P_{j,k}$ do not comply with the standard because the current version of DIN 2244 does not contain any specifications regarding the counting method.

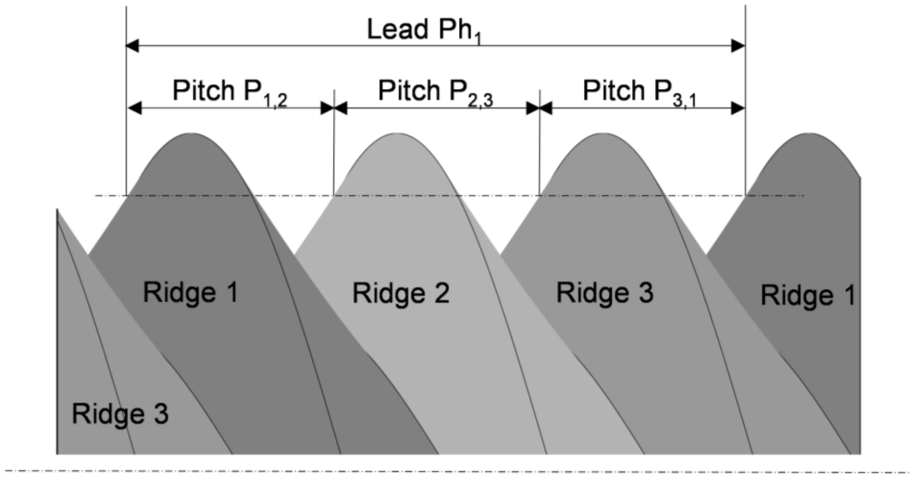

Figure 3: Pitch and lead on a three-start external thread. The parameters are only shown for one flank direction. For the flanks in the other direction, additional parameters apply.

When carrying out measurements on coordinate measuring machines (CMM) with contact on two flanks, or in measurements with simulated two-flank contact using the stylus method (see chapter 4.2), the parameters that are typically determined are *two-flank lead* and *two-flank pitch* (see [10], 3.3.17 and 3.3.19). Given that these parameters are explicitly defined as determining quantities in DIN 2244 and ISO 5408, the specifications stated in calibrations and comparison measurements should also refer to these parameters to avoid misunderstandings.

4 Common measurement methods – overview

This section presents the most frequently used methods for the calibration of threads. The explanations serve as basis for the discussion of the respective measurement uncertainty influences and traceability proofs in chapters 5 and 6.

4.1 Three-wire and two-ball method

Both the three-wire method and the two-ball method are preferably used on length comparators. The three-wire method is only suitable for measuring external threads (thread plug gauges). The indicated value m is measured; it is needed to calculate the pitch diameter. The wires are usually made of hard metal (gauge steel) or, more rarely, of ceramic and are each used to form three wires with as equal a diameter as possible. There are two ways of using the wires. One is to use the wires in a freely suspended position; alternatively, they are offered attached in holders with a hole for mounting on the measuring bolt of a length comparator. In both cases, it must be ensured that each of the wires is in contact with both flanks of the thread (see Figure 4).

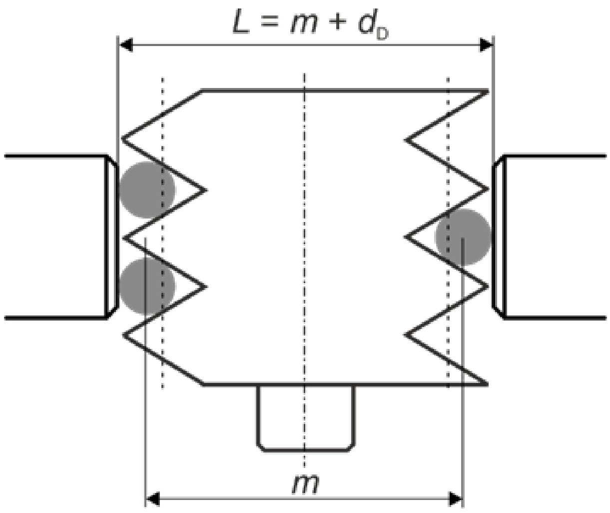

Figure 4: Measurement of the indicated value m on a single-start external thread using the three-wire method

When using a holder, it is important that the wires can move freely and do not get jammed in the holder. Two wires on one side and one wire on the opposite side are inserted into the thread gaps of the same thread so that no transverse forces occur during measurement. The diameter of the measuring wires must be chosen in such a way that the probing of the thread flanks is carried out as close as possible to the nominal pitch diameter. The optimum wire diameter d_{o} is determined by the following equation (1) (see [6]):

$$d_{\mathrm{o}} = \frac{P}{2 \cdot \cos \alpha/2} \quad (1)$$

The greater the difference between the actual wire diameter and the optimum wire diameter, the less accurate the determination of the pitch diameter. As a result, the measurement uncertainty increases (see chapter 5). With a defined measuring force of the length comparator, the indicated value is measured across the measurement wires L in two axial sections (A-B and C-D) and, depending on the length of the thread, in at least two planes along the thread axis. This measurement strategy is also described in VDI 2618 part 4.8 [2]. The indicated value m, which is defined as the distance of the central points of the probing elements (here measurement wires), is calculated from each of the measured lengths L minus the mean wire diameter of the three wires d_{D}.
The pitch diameter is determined by means of a software, according to Berndt's algorithm [4][6]. Moreover, it has to be considered which of the three pitch diameters defined in [10] and [11] is to be calculated. Depending on the values inserted for lead and thread angle – nominal or measured values – it is possible to calculate the simple pitch diameter $d_{2\mathrm{S}}$, the pitch diameter d_2 or the virtual pitch diameter $d_{2\mathrm{P}}$ (see chapter 3).

The two-ball method is used for measuring internal threads. In coordinate metrology, however, it is also used for measuring external threads. To select the suitable probe ball diameters, equation (1) is to be applied, analogous to the three-wire method. The double ball probes (also called T-shaped probes or two-ball probes) required for measurement consist of a vertical shaft of which one side serves for being attached to the measuring system, and whose other side is equipped with a sidewards protruding pin.

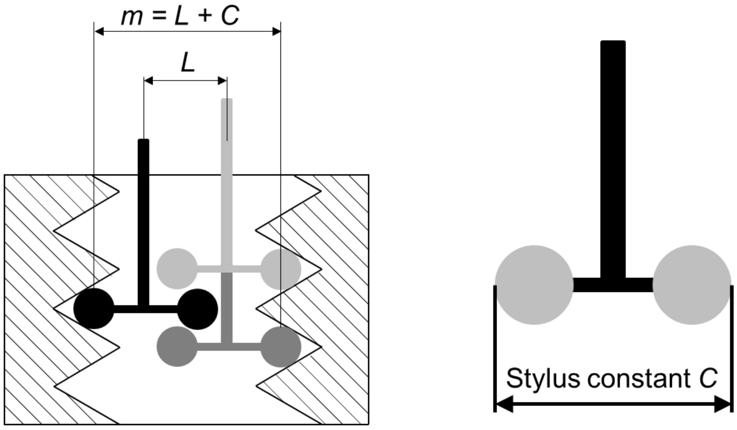

Figure 5: Measurement of the indicated value m on a single-start internal thread using the two-ball method

A ball is attached to each end of the pins. Usually, these balls are made of ruby. However, steel or diamond-coated balls can also be used. The distance between the two balls determines the smallest measurable thread size when measuring internal threads. Here, the core diameter of the internal thread must be taken into account to enable the double ball probe to be inserted in the thread ring. The distance between the two balls is called probe constant C. Prior to the measurement, it must be adjusted on the thread using an adjusting ring or a gap measurement standard (see chapter 6). Moreover, the balls of the double ball probes must be calibrated in diameter and shape.
As is the case with external threads, the indicated value m is measured and then the pitch diameter is calculated. For this purpose, a measuring point located between two thread flanks and touching both flanks (two-flank position) is recorded. Here, it must be ensured that the probing ball touches both thread flanks with as equal a measuring force as possible. In case of a length comparator, the system must have been brought into equilibrium and the reversal point determined when taking over the measuring point. This procedure must be repeated in the next thread gap of the same thread on the same side and on the opposite side (see Figure 5). The rest of the procedure corresponds to the procedure for the three-wire method.

4.2 Profile method

In tactile surface metrology, the profile (or stylus) method is used to determine roughness parameters and to measure contours such as thread profiles. This method allows contacting 2D data acquisition by means of a probe arm and probe tip via two orthogonally aligned measuring axes. In the context of thread measurement technology, the term “thread scanner” is also used.
As a rule, a contour to be measured is scanned in the direction of the *x*-axis of the measuring device at a constant speed (see Figure 6). Due to the changing *z*-information of the profile, the constant *x*-feed leads to fluctuating scanning speeds along the profile. With constant sampling frequency this results in constant measuring point distances in *x*-direction, but not along the profile. For very steep profile flanks, the sampling frequency should therefore be increased if necessary, or the feed rate in the *x*-direction should be reduced if the sampling frequency is constant in order to guarantee sufficient measuring point density. There are however contour measuring devices which are equipped with a decoupling of *x*- and *z*-axis to ensure constant measuring point distances along the profile.
To record profile measurements on threads approximately in the axial section, the thread to be characterised is fixed horizontally. If, for example, a prism holder is used, the frontal

reference surface of the holder is pushed against a planar stop of the thread scanner. Ideally, this stop is aligned plane-parallel to the *yz*-plane of the scanner. Parallelism of the thread axis and the *x*-axis of the scanner is desirable but cannot be guaranteed (tilting of the thread in the clamping system, form deviation of the thread, …).
In a final alignment step, the clamped thread including the clamping system are moved orthogonally to the measuring plane of the scanner until the thread axis and the *xz*-plane of the scanner are approximately coplanar. For this purpose, the upper or lower reversal point of the thread can be determined with the help of an additional axis (non-measuring) that is orthogonal to the *xz*-plane of the scanner. To derive diameter quantities based on 2D profile measurements, it is necessary to measure from above and below, using a probe arm with two probe tips. This means that in the ideal case, when measuring along the *x*-axis, the measurement will also be made along the axis of the thread. In practice, however, this can never be completely guaranteed due to misalignment of the thread so that the ideal axial section of the thread can only be approximated.

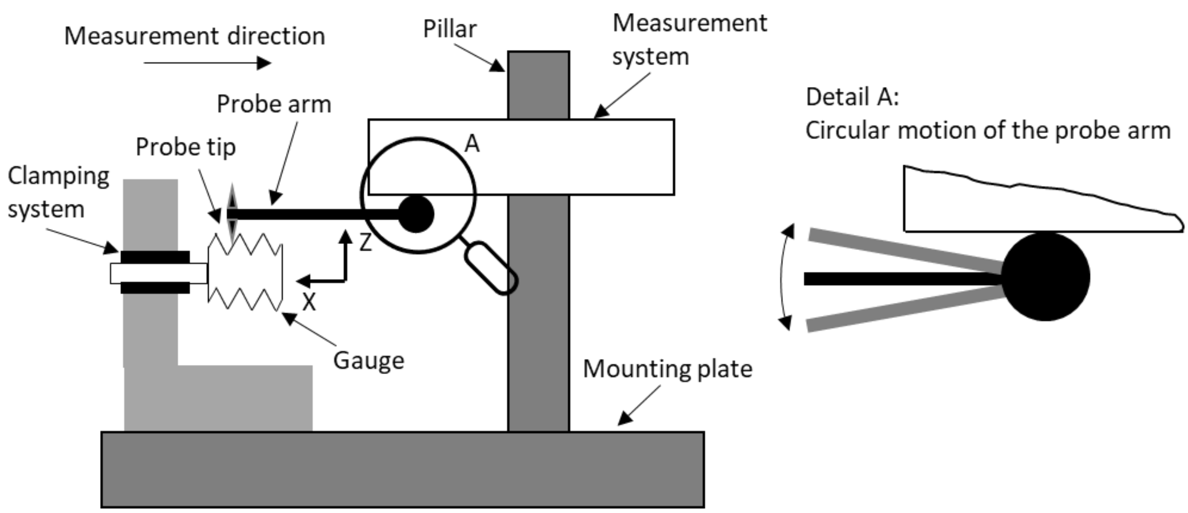

Figure 6: Measurement of a single-start external thread on a stylus instrument

Usually, the measurement values are taken by means of an inductive position-measuring system, recording the profile of the measured object. In many stylus instruments, the probe arm performs a circular motion (see Figure 6). This circular motion depends on the length of the probe arm and the profile height of the thread and must be taken into account by the evaluation software of the measuring device. Due to the up and down movement of the probe, the sliding friction between probe tip and workpiece does also play a role. This influence can be reduced by suitable selection of the probe material. Probe tips are made of carbide, diamond, or ceramic, for example, and are offered in various designs. Depending on their application, probe tips are manufactured with radii between 2 µm for roughness measurements and up to 100 µm for contour measurements. In thread measurement, tapered tips or probe tips with a taper flattened on one side are used for small thread angles, depending on the thread profile. The probe's form deviation as well as any possible bending of the probe arm due to probing are taken into account on the basis of calibration routines and suitable radius correction factors. Due to wear of the probe tip, it is necessary to carry out this type of measurement/calibration routine on a regular basis.

4.3 3D measurement method

A measurement and evaluation method for the areal as well as the holistic characterisation of helical geometries – which of course also include threads – has been developed at PTB in a joint project with partners from industry and calibration laboratories. By means of this procedure, the actual geometry can be described with the help of a parameterised model, from which the typical parameters can be derived. Moreover, this procedure provides a topographical illustration of the deviations along the entire helical surfaces. The result of the areal measurement with five radially distributed traces on the thread flank is shown in Figure 7 as 3D graphic and in Figure 8 as development of a surface (developed view).

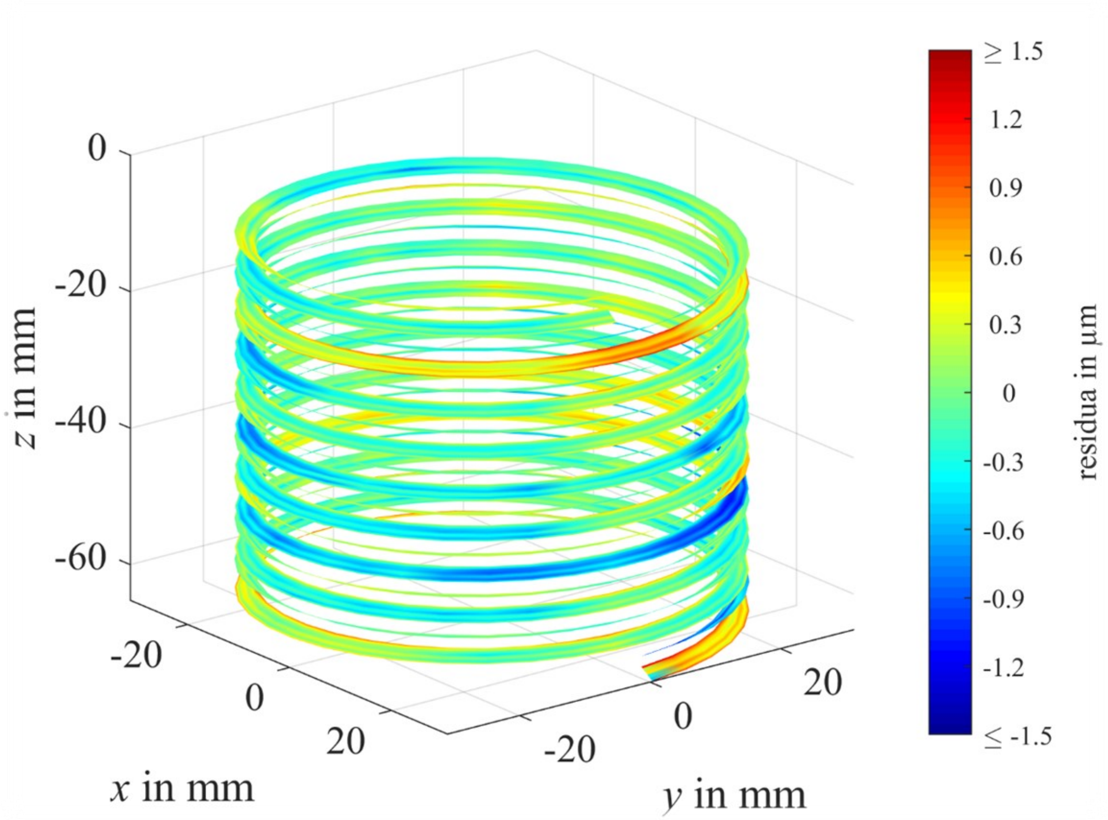

Figure 7: Illustration of the result of the areal thread measurement using a Coordinate Measuring Machine (CMM)

The areal measurement of the thread geometry, however, requires a more extensive measuring equipment. While for one and two-dimensional measurements, measuring devices with only one or two measuring axes are used, a third or fourth measuring axis is added for three-dimensional measurements. These axes can be translatory and or rotatory (rotary table). Here, the use of universal coordinate measuring machines is a suitable option, although these coordinate measuring machines require greater programming effort. The advantage of a rotary table is that the screw surface can be scanned continuously. This provides information about the course of the lead which, for example, reveals periodic pitch errors that cannot be detected in axial section measurements. If the measurements are carried out on different radii, sufficient data is also obtained to evaluate the thread flank. This means: the more measurements are carried out in radial direction, the more reliable the measurement result of the straightness of the thread flank and the flank angle. The evaluation of the measurement data is carried out by means of an algorithm that fits the parameterised thread geometry into the captured measurement point cloud as best as possible [13], [14]. The geometry parameters of this best-fit element can then be converted into the thread parameters [15].

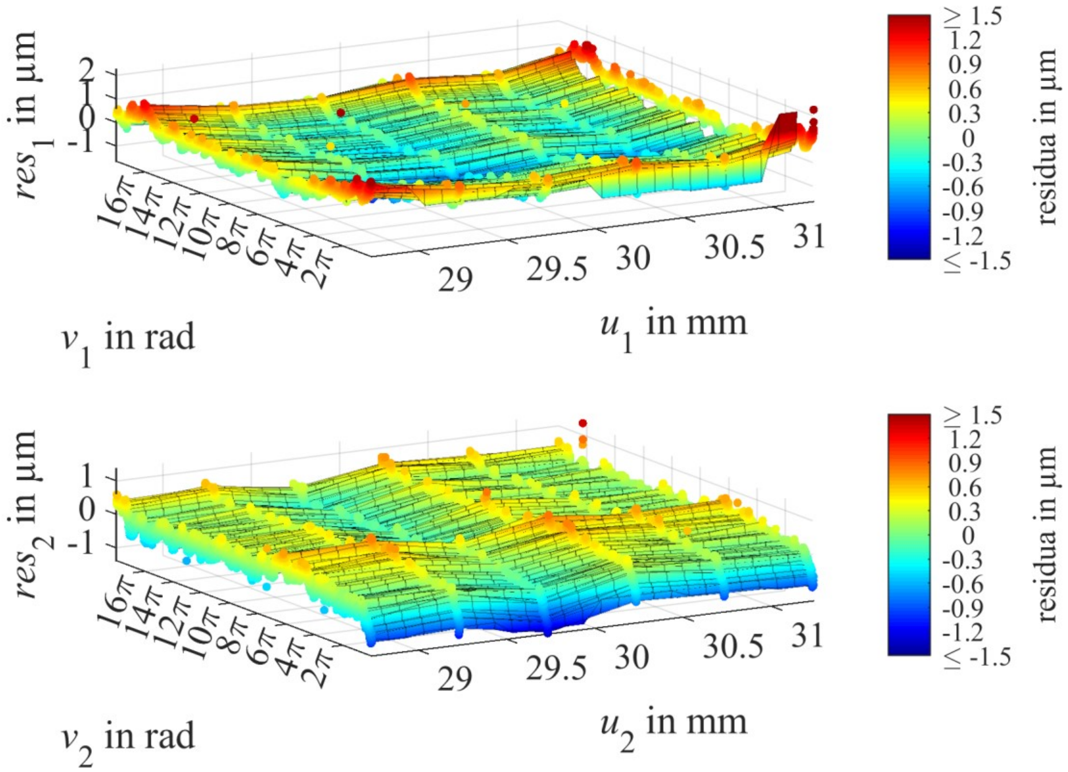

Figure 8: Illustration of the measurement result of the areal measurement (developed view of both thread flanks)

4.4 Optical measurement methods

Optical measuring technology is still rarely used in thread measurement. Occasionally, transmitted light microscopes are used; these can be used for the calibration of external threads. However, this measurement method involves difficulties such as shadows or reflective surfaces which falsify the measurement result and lead to higher measurement uncertainties [16]. For internal threads, it is necessary to first make an impression of a segment of the internal thread, which can then be measured in the same way as the external thread using the transmitted light method. However, this method can only be used to determine the flank angle and pitch.

Imaging processes as, for example, the focus variation method offer the advantage of a fast measurement with high resolution and a non-contact measurement [17]. In the future, the areal measurement of the screw surface will offer good possibilities for the calibration of thread gauges. Unfortunately, developments have not yet reached the point where the measurement methods can be implemented into practice.

4.5 Recommendations regarding the scope of calibration

To measure the desired thread parameters, the described measuring methods can be combined in different ways. The purpose of this chapter is to give a recommendation on how to apply these methods, taking into account the existing guidelines [2], [3] and [6], and which thread parameters have to be measured.

At present, the most common instructions for thread calibration are the EURAMET cg-10 as well as the aforementioned VDI guidelines. These guidelines are generally considered to be more or less identical in content; they are often mentioned simultaneously. However, on closer examination, the two documents differ in several respects.
EURAMET cg-10 describes the determination of the different pitch diameter concepts as well as the associated measurement uncertainty by categories and lists the thread parameters to be measured in each case. In addition, it also lists the parameters that are to be included in the measurement uncertainty. Examples for calculating the pitch diameter in the individual categories provide practical information for preparing the measurement uncertainty budgets.
The VDI guidelines place more focus on the practical application regarding the preparation and execution of the thread measurement, but without describing exactly how the pitch diameter is measured or calculated. However, the options given in the VDI guidelines enable the customers of the calibration laboratories to select “packages” of measurement parameters, thus ensuring an uncomplicated and unambiguous placing of their calibration order. Even the measurement quantities that do not directly belong to the determination of the pitch diameter, such as core and outer diameter, are taken into account. These quantities are tolerated by the thread standards and do also have an influence on the mating ability of the thread.
For the reasons mentioned, these two guidelines are not fully comparable. However, when applied correctly, together they provide a good basis for correctly identifying and evaluating the complex geometry of the thread.
In the following, the three essential categories for thread calibration are described in more detail. They are arranged according to measurement effort, and widely correspond to the calibration options specified in the guidelines.

Check for wear
Recalibrations, in which previously measured thread gauges are to be checked for wear, can be carried out with considerably less effort. The only thing to be determined is the simple pitch diameter from the measurement of the indicated value, using the value for the thread profile angle known from a previous calibration; this can be done, for example, on a length comparator according to the three-wire or two-ball method.

Complete measurement of the geometry
For a complete geometry measurement, the following parameters must be determined:

- lead
- pitch (for multi-start threads)
- both thread flank angles
- outer and core diameter
- single pitch diameter
- pitch diameter

Determination of these parameters requires measurement on a contour or coordinate measuring machine.

As already described in chapter 3, a reliable determination of the virtual pitch diameter according to DIN 2244 or ISO 5408 is not possible with the methods and devices typically used in thread measurement. Instead, areal measurement data are required along the entire screw surfaces as well as a mathematically complex calculation of the corresponding minimum circumscribe and maximum inscribe thread. The correction amounts described in EURAMET cg-10 only provide an approximate solution and, moreover, are only described for symmetrical threads. Their application can therefore not be recommended here. See also explanations in [1].

5 Measurement uncertainty

The measurement uncertainty is a measure indicating the imperfection of a measurement process. In the *International vocabulary of metrology* (VIM) [18] as well as in its German translation [19] the uncertainty of measurement is defined as a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”. The result of a measurement generally consists of a measured value and the associated measurement uncertainty:

> Measurement result = measured value ± measurement uncertainty

To determine the measurement uncertainty, the following steps are required regardless of the measurand under consideration:

1. Description of the measurement: measurement method, auxiliaries, …
2. Identification of the input quantities
3. Mathematical model of the measurement: output quantity = function of the input quantities
4. Determination of the standard uncertainty of all input quantities from measured values, calibration certificates, literature, former measurements, …
5. Calculation of the result and the associated standard uncertainty: output quantity with combined standard uncertainty
6. Calculation of the expanded measurement uncertainty
7. Indication of results: measured value with measurement uncertainty

5.1 Influence quantities

For a reliable determination of the measurement uncertainty, all influence quantities of the measurement process must be known. As shown in Figure 9 in a simplified way, these can be divided into different categories. The measurement strategy as well as the measuring instrument used – including the probing element – play an important role. In addition, the nature of the thread to be measured and the ambient conditions must be considered. And finally, there is also the influence of the operator on the measurement result. Basically, it must be distinguished whether the uncertainty influences lead to systematic (VIM 2.17) or random (VIM 2.19) errors. The systematic errors form part of the measurement error which in a series of measurements either remains the same or changes in a foreseeable way. If the systematic errors are known, they must be corrected.

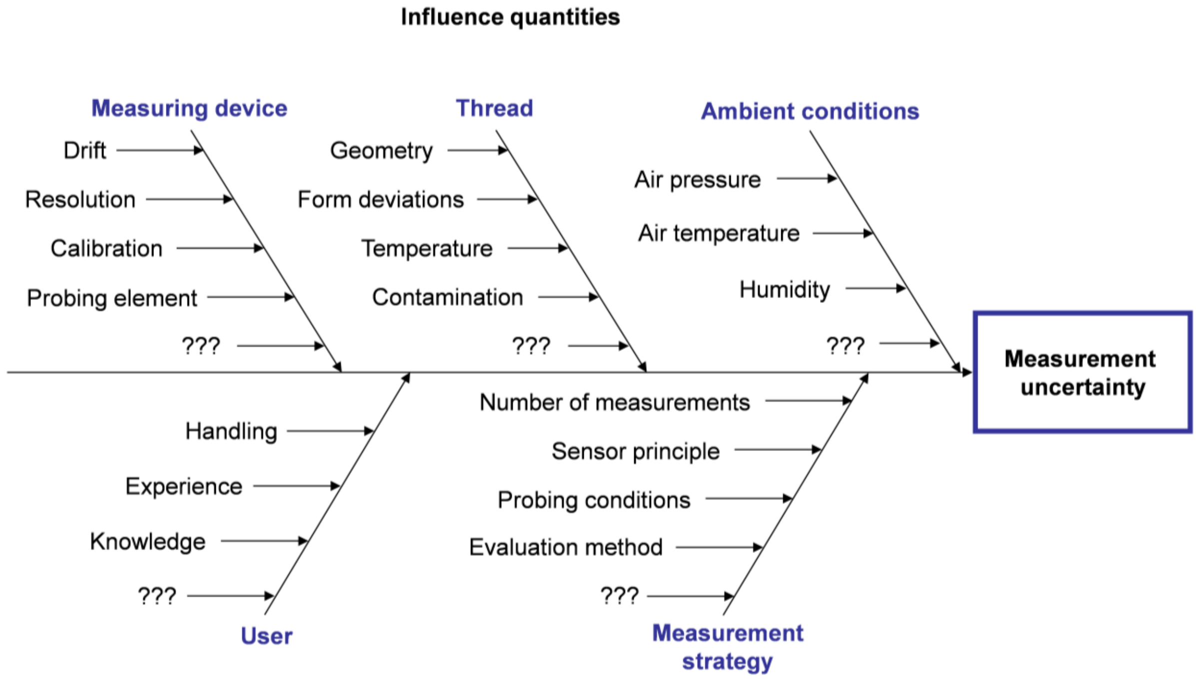

Figure 9: Ishikawa diagram to illustrate the influence quantities acting on the measurement process

The choice of the measurement method as well as the choice of the measuring instrument play a decisive role with regard to the measurement uncertainty. Depending on the method used, different influence quantities have to be considered. For example, different auxiliary devices with specific measurement uncertainties are used. And the traceability of the measuring instrument also has a direct influence on the uncertainty of the calibration. This uncertainty might be reduced by a correction through substitution measurement. Various influence quantities can be derived from the measurement procedures described in chapter 4. These are listed in the following sections. These sections present the most important contributions to the measurement uncertainty and should be definitely taken into account. Furthermore, there may be specific influences in each laboratory which have to be individually identified. For example, a special type of calibration or the individual mounting of sensing elements may cause different influences.

5.1.1 Influences on the length measuring device: three-wire and two-ball method (1D)

When using the three-wire or two-ball method, measurements are carried out with in the two-flank position (two-flank contact) (cf. Figure 10). The influences on the measurement uncertainty of the different flank diameter concepts are described in EURAMET cg-10 [6]. More detailed descriptions and background information can be found in the original papers by Berndt [4] and in the report by Kochsiek and Lerch [5] which compare different methods. Nonetheless, the most important contributions will be briefly discussed here.

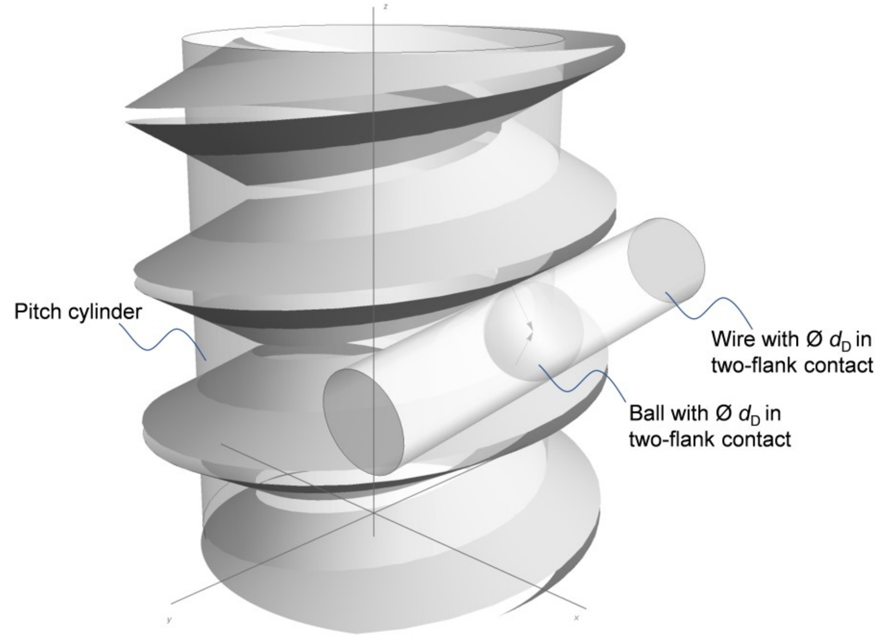

Figure 10: Measuring wire and ball in two-flank contact on the pitch diameter of a symmetrical external thread**.** The contact points of wire and ball are identical and lie in a normal section of the thread.

Measurements according to the three-wire or two-ball method are mainly based on the exact knowledge of the probe's diameter. Deviations in diameter of the ball or wire influence the determination of the pitch diameter. For quantifying this influence, it is necessary to examine the position in which the probing element is applied to the thread. Typically, this is done in the axial section of the thread. It is, however, important to understand that in case of two-flank contact, the contact points of the ball or the wire never lie in the same axial section. Instead, both contact points lie in the same normal section of the thread, that is, in a plane perpendicular to the thread flanks. Normal section and axial section are only the same if $Ph = 0$, which of course is never the case with a thread (see Figure 11).

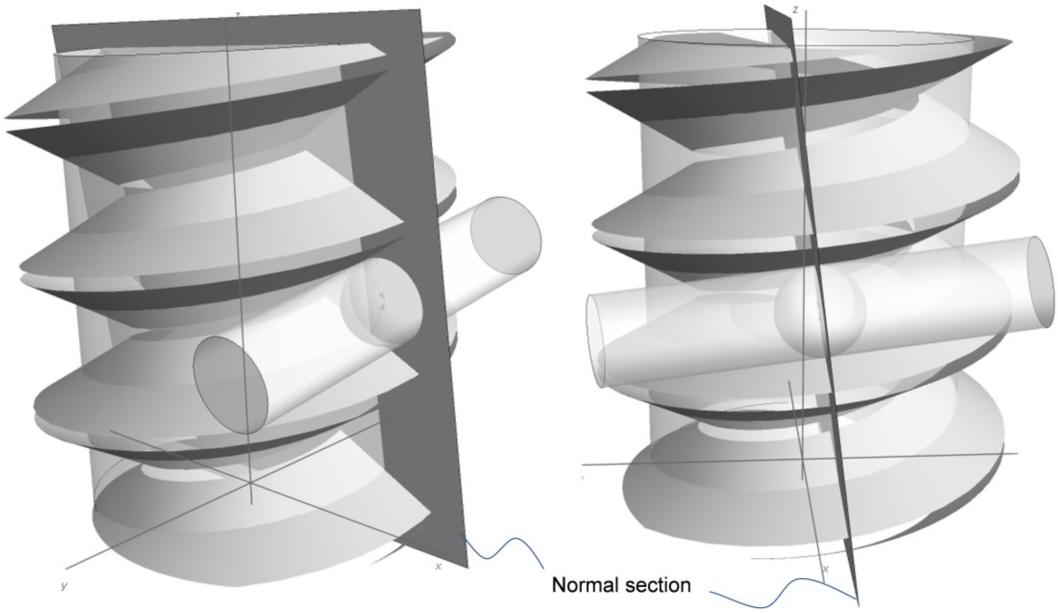

Figure 11: Illustrated are two views of the same figure already depicted in Figure 10; here, the normal section belonging to the contact points has been added. In the right-hand view it can be clearly seen that the contact points of the ball and wire lie in this normal section and that this plane is inclined with respect to the axial section through the centre of the ball, which contains the *z*-axis.

To calculate the pitch diameter from the metrologically determined indicated value m (see Figure 4 and Figure 5) EURAMET cg-10 initially assumes, in accordance with Berndt's theory, an infinitely thin circular disc with diameter d'_{D} which touches both flanks in the same axial section (see Figure 12).

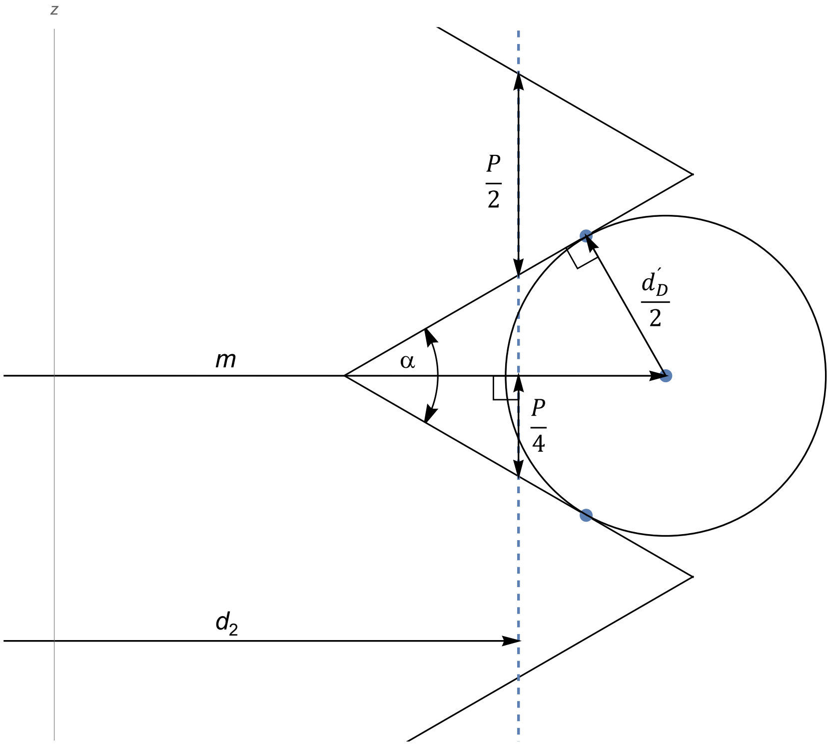

Figure 12: An infinitely thin circular disc with diameter $\boldsymbol{d}'_{\mathbf{D}}$ touches both flanks of the thread in the same axial section. Here, the pitch diameter d_2 results from the indicated value m by simple trigonometric calculations in the two right-angled triangles shown.

In this case, Figure 12 directly yields

$$d_2, D_2 = m \mp d'_{\mathrm{D}} \frac{1}{\sin\alpha/2} \pm \frac{P}{2} \cot\alpha/2\,, \qquad (2)$$

with the upper sign referring to external threads (plugs, d_2) and the lower sign to internal threads (rings, D_2).

Now, moving from the infinitely thin circular disc to a ball or a wire with diameter d_{D} (the contact points are identical for ball and wire of the same diameter, see Figure 10), an additional term must be added to equation (2) which takes into account the displacement of the contact points from the plane of the axial section to the normal section. An exact mathematical expression for this correction of the contact position cannot be given in closed form since the relationship between the diameter of the probing element and the contact circle is given in the form of transcendental equations. The determination requires a solution by an iterative algorithm such as originally developed by Prof. Berndt and outlined in EURAMET cg-10 [4][6]. Derivation by means of a 3D model can alternatively be carried out according to [15], using the standard's vectors and analogous to the procedure used in [20]. For users in calibration laboratories and similar institutions, it might be of interest to know that PTB provides a simple implementation of the algorithms according to Berndt which is able to perform the exact calculation of the pitch diameter for cylindrical threads (rings, plugs, symmetrical or asymmetrical, single or multi-start) after entering the required geometrical characteristics. This Java programme can be downloaded free of charge from the PTB website https://www.ptb.de/cms/ptb/fachabteilungen/abt5/fb-53/ag-533/ptb-gewinde-software.html (see Figure 13).

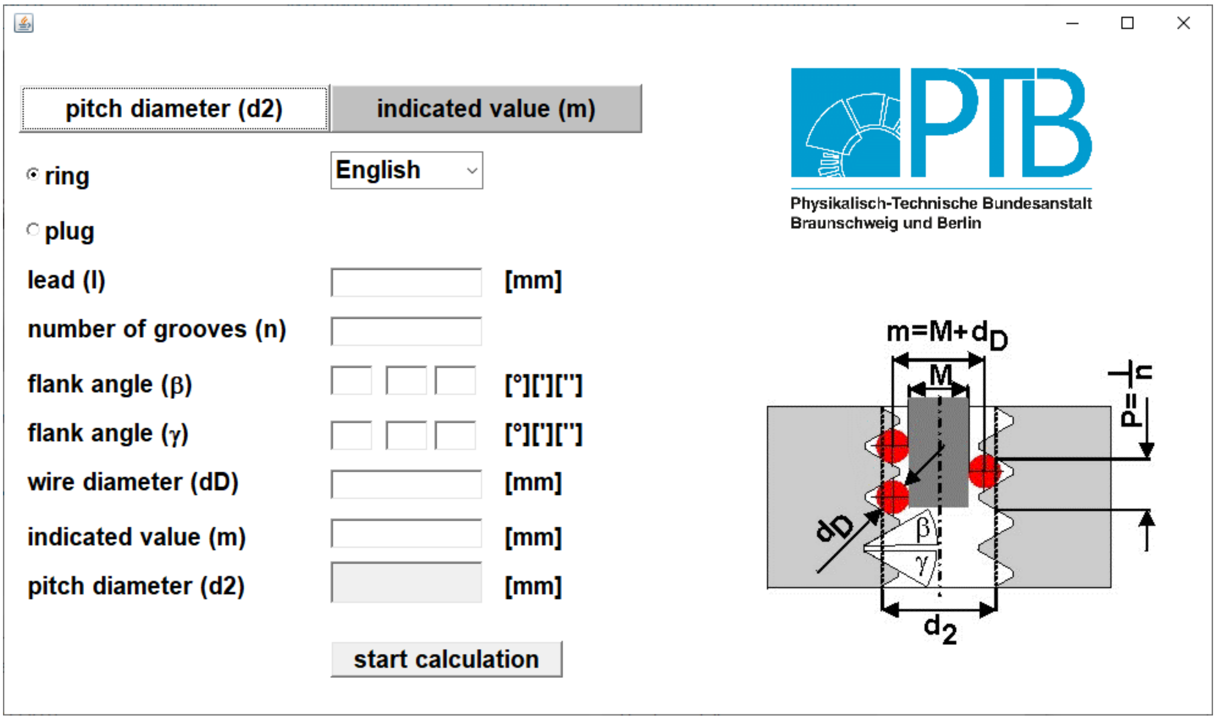

Figure 13: Screenshot of the PTB programme (available free of charge) for the exact calculation of the pitch diameter according to Berndt without consideration of the flattening caused by the probing force.

For an approximate solution, however, EURAMET cg-10 gives an approximation of the rake correction, which in some cases (symmetrical profile, pitch not too large, flank angle not too small) provides useful solutions. Equation (2) thus becomes

$$d_2, D_2 = m \mp d_{\mathrm{D}} \frac{1}{\sin \alpha/2} \pm \frac{P}{2} \cot \alpha/2 \mp A_1 \qquad (3)$$

with the approximative rake correction

$$A_1 = \frac{d_{\mathrm{D}}}{2} (\tan \psi)^2 \cos\frac{\alpha}{2} \cot\frac{\alpha}{2}, \qquad (4)$$

with ψ designating the helix angle of the thread with

$$\tan \psi = \frac{P}{\pi D_2} \quad \text{bzw.} \quad \tan \psi = \frac{P}{\pi d_2} \qquad (5)$$

The limits of this approximate solution are shown in the appendix of EURAMET cg-10 with some numerical examples.

Equation (3) can now be used together with (4) and (5) to quantify the influence of the probe element diameter on the determination of the pitch diameter. If we also take into account the relationship $m = L - d_{\mathrm{D}}$ from Figure 4 for external threads – since the first thing to be determined on the length comparator is the dimension L – the following results:

$$\frac{\partial d_2}{\partial d_{\mathrm{D}}} = -1 - \frac{1}{\sin \alpha/2} - \frac{1}{2} (\tan \psi)^2 \cos\frac{\alpha}{2} \cot\frac{\alpha}{2} \qquad (6)$$

This expression indicates the sensitivity of the pitch diameter of an external thread to deviations in the probe element diameter (sensitivity coefficient, see GUM [22]). For a typical thread profile angle of $\alpha = \pi/3 \triangleq 60°$ the result is $|\partial d_2 / \partial d_\mathrm{D}| \approx 3$. A deviation from the calibration value of the probe element diameter therefore affects the determination of the pitch diameter here by a factor of approximately 3!

The probing element should therefore always be calibrated in diameter and shape with an adequate number of measuring points and using an angular range appropriate to the measuring task. Sections 6.2.1 and 6.2.2 offer a detailed description.

Accordingly, equation (3) yields the sensitivity coefficients for the pitch P and the thread flank angle $\alpha/2$ (for symmetrical threads). This is done as follows:

$$\frac{\partial d_2}{\partial P} = \frac{1}{2}\cot\frac{\alpha}{2} \tag{7}$$

and

$$\frac{\partial d_2}{\partial(\alpha/2)} = \frac{\cos\alpha/2}{(\sin\alpha/2)^2}(d_\mathrm{D} - d_\mathrm{o})\,, \tag{8}$$

Here, the term from the rake correction has been neglected in both cases. In equation (8), d_o is the optimal diameter of the probe ball given in equation (1) which only results through this relation, since obviously the sensitivity coefficient $\partial d_2 / \partial(\alpha/2)$ for $d_\mathrm{D} = d_\mathrm{o}$ disappears. For the above example of $\alpha = \pi/3 \triangleq 60°$, we obtain the numerical values $|\partial d_2 / \partial P| = \sqrt{3}/2 \approx 0{,}866$ and $\partial d_2 / \partial(\alpha/2) = 2\sqrt{3}(d_\mathrm{D} - d_\mathrm{o}) \approx 3{,}464(d_\mathrm{D} - d_\mathrm{o})$. Here, α must always be indicated in rad.

These calculations and numerical examples clearly show how important the exact knowledge of the thread geometry (pitch and angle) is for a reliable determination of the thread flank diameter. Against this background it also becomes clear why thread gauges should always be calibrated according to option 2b or 3 according to EURAMET cg-10 (or options 4 and 5 in [2] or [3]). The other options do not consider important influence quantities!

With each probing process, the measuring force causes an elastic deformation of the probe element. The extent of this deformation depends on the materials being used, the probing force and the geometry of probe element and thread. The elastic modulus for the materials used is also taken into account. Depending on the measuring method, it is possible that the deformation which occurs during calibration compensates the deformation during thread measurement. EURAMET cg-10 describes how the correction of the deformation can be approximately calculated according to Hertz [6].

In addition, the sliding of the probe element along the flank of the thread, until touching both flanks, causes friction. This friction causes a flattening of the probe ball surface, which in turn causes the probe to enter deeper into the V-groove thus causing a deviation of the measuring point. Especially when measuring in the two-flank position, this has a great influence as the friction always occurs at the same two points of the probe element Figure 14 shows the situation with a probe in two-flank position, with one ball probe located in a gap. Ideally, the measuring point is recorded with the forces at the contact points being the same, i.e.

$$F_{\mathrm{N1}} = F_{\mathrm{N2}} = \frac{F}{2 \cdot \sin(\alpha/2)} \tag{9}$$

With a thread profile angle of 60°, this yields a force equilibrium of $F = F_{\mathrm{N1}} = F_{\mathrm{N2}}$. Consequently, the ratio is

$$w_{v0}(F_{\mathrm{N}}) = \frac{w_0(F_{\mathrm{N}})}{\sin(\alpha/2)} \tag{10}$$

With a thread profile angle of 60°, this means that the distance travelled by the ball in the direction of measurement $w_{v0}(F_{\mathrm{N}})$ is twice as great as the distance $w_0(F_{\mathrm{N}})$ in the direction of force, due to the flattening. With smaller angles, the influences are even greater [21].

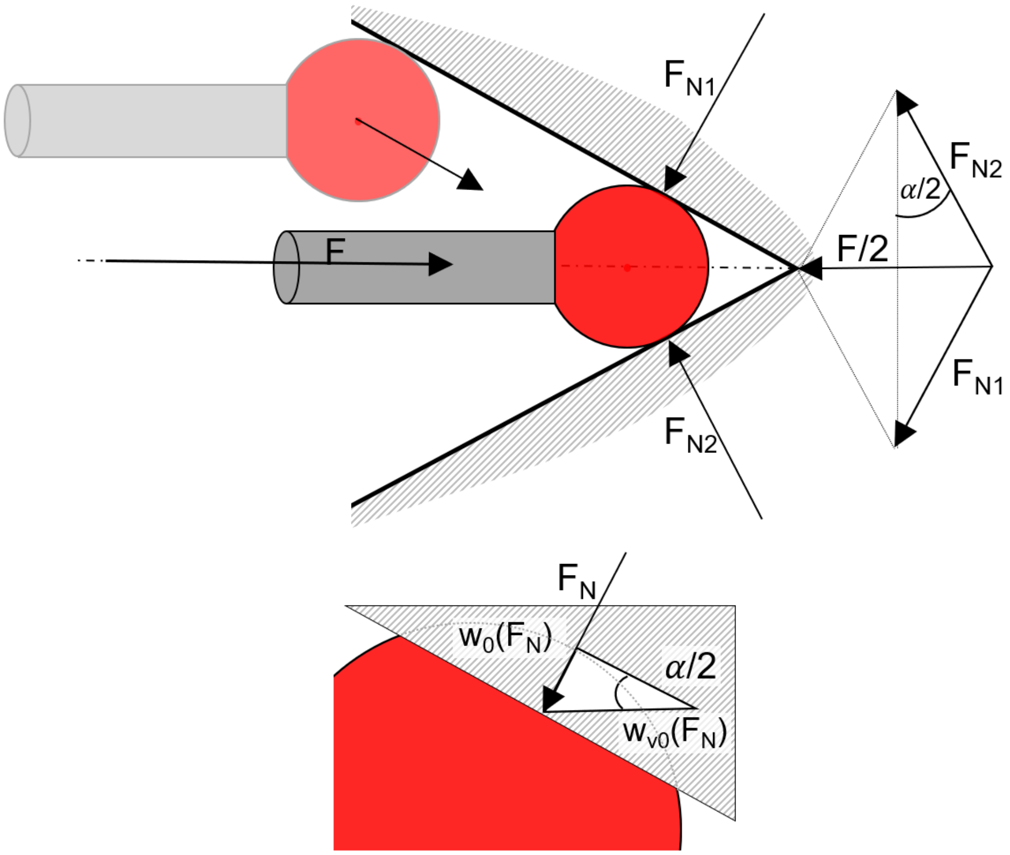

Figure 14: Flattening due to wear in two-flank contact

To deal with this measurement uncertainty influence, the probe elements should be checked regularly for damage and contamination. This can be done under a microscope, for example. During measurements, the probing elements are subject to considerable operational and mechanical stress, a frequently recurring source of error which can be reduced rather easily.

The following is a summary of the most important influence quantities when measuring thread gauges on a length measuring device.

(Simple) pitch diameter

- Measured value, measured displacement of the probing element
- For double ball probes, the probe constant is determined by measurement, for example on a ring gauge. The result then includes the standard uncertainty of the reference standard as well as influences from the measuring process.
- Probe diameter from calibration certificate
- Influences resulting from pitch and thread flank angle of the thread
- Rake correction
- Elastic deformation due to measuring force
- Form deviations due to imperfection of the thread gauge

For the **virtual pitch** the following corrections have to be added:

- Pitch correction
- Correction of the thread flank angle

External diameter at the external thread or core diameter at the internal thread
In this case, the influences to be taken into account are basically the same as for measuring the pitch diameter. The difference between these measurements is the way in which the probe elements are positioned on the thread. While the pitch diameter is measured in two-flank contact, there is only one contact point here. This must be taken into account when calculating the input quantity.

Usually, the **pitch** and the **angles** are not measured on the length measuring device. This equally applies to the **outside diameter on the internal thread** and the **core diameter on the external thread.**

5.1.2 Influences on the contour measuring device: contact stylus method (2D)

Flank diameter, outer diameter, and core diameter

- Correction after intermediate calibration in the approximate diameter range with a setting ring (substitution measurement)
- Form deviations of the thread gauge
- Temperature and coefficient of linear expansion of thread gauge
- Temperature and coefficient of linear expansion of glass scales
- Radius and feed deviation due to movement of the probe arm
- Alignment of thread in clamping system → Measuring plane of scanner may not be coplanar with thread axis
- Search for reversal point of the thread by the operator → Measuring plane of scanner may not be coplanar with thread axis
- Wear of the probe tip
- Calibration of the probe tip by the operator, especially when using probe arms with two probe tips for measuring from below and above (positional relationship of the probe tips in *x* and *z* direction), form deviation of the calibration standard
- Adjustment of the measuring force
- Dirt (on test specimen, probe tip, glass scales, ...)
- Determination of the test plane by the operator or alignment of the threads according to the test plane marking, for conical threads: form deviation on thread face
- Evaluation algorithm: threshold value for filtering of thread groove and thread tip
- Internal rounding errors due to software and measured value output

Still to be added for **pitch** and **thread angle**:
- Axial radius deviation
- Deviation of the *x*-axis of the measuring device to the thread axis

5.1.3 Influences on the coordinate measuring machine: two-ball method (1D) in combination with profile scan (2D)

There are different methods to calibrate a coordinate measuring machine. For the calibration of a thread gauge according to VDI/VDE/DGQ 2618 Part 4.8 and 4.9, a double ball probe can be used to measure the pitch diameter, the outer diameter on the external thread or the core diameter on the internal thread and the pitch. It is possible to measure the external diameter on the internal thread or the core diameter on the external thread with a tip probe. The angles are measured by scanning the flanks in the axial sections. Here, a substitution measurement with reference standards such as gauge blocks, smooth ring and plug gauges is a good way of reducing the measurement uncertainty and determining a correction value. However, a more suitable method would be to use a calibrated thread gauge, which not only corrects the dimension, but also simulates the probing conditions on the test specimen as closely as possible.

To determine the **pitch diameter**, at least the following influences must be considered:
- Measured value
- Probe ball diameter from calibration certificate
- Depending on the calibration option, the nominal values, measured values or the values from the calibration certificate are used for slope and profile angle
- Contact correction and the flattening must be taken into account according to the probe element used
- Imperfection of the measuring process: This contribution includes the form deviations of the thread gauge and other device- or process-dependent influences which have not been considered so far and is based on experience gained through observations of the measuring process.
- Temperature difference between substitution standard and test specimen

Outside diameter on the external thread or core diameter on the internal thread
These diameters are measured with ball probes. The influencing quantities are the same as for the pitch diameter. Here, too, it is important to note how the probing is carried out in detail.

The **pitch** is determined from the points measured above. Thus, the influence quantities are the same.

Outside diameter on the internal thread or core diameter on the external thread
These diameters are measured with tip probes at the thread groove.
- Displayed value without correction
- Reference standard from calibration certificate and measured value
- Imperfection of the measuring process: This contribution includes the form deviations of the thread gauge and other device- or process-dependent influences that have not yet been taken into account and is based on experience through observations of the measuring process.

Thread angle

The angles are also measured using the tip probe

- Measured value flank angle
- Contribution from workpiece position, wobble
- Contribution from form measurement
- Contribution from probe calibration
- Contribution from measuring device linear element

5.1.4 Influences on the coordinate measuring machine: 3D measuring method with rotary table

There is a new method that allows a holistic measurement of the thread gauge (see section 4.3, [14]). The 3D measurement on the coordinate measuring machine is carried out using a rotary table, with the probing being performed in single-flank contact.

Flank diameter

- Flank diameter from software
- Probe ball diameter from calibration certificate
- Probe ball diameter from probe calibration
- Angle and pitch as above
- Length-dependent contribution CMM
- Contribution from substitution measurement
- Contribution rotary table
- Coefficient of linear expansion of the test specimen
- Temperature of the test specimen
- Thermal expansion coefficient of the substitution standard
- Temperature of the substitution standard

Lead

- Measured value
- Contribution from form measurement
- Contribution from probe calibration
- Measurement uncertainty Coordinate Measuring Machine
- Contribution measuring instrument constant element
- Contribution of measuring instrument linear element
- Contribution of temperature change during measurement
- Coefficient of thermal expansion of the test specimen

Thread angle

- Measured value
- Contribution from workpiece position, wobble
- Standard deviation flank form
- Contribution from rotary table deviations
- Contribution from probe measurement (position deviation)

5.2 Procedure for determining the measurement uncertainty

To determine the measurement uncertainty, very different approaches exist. The international guide ISO/IEC Guide 98-3:2008-09 “Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM)" is identical with the freely available guide JCGM 100:2008 "Evaluation of measurement data - Guide to the expression of uncertainty in measurement" published by the Joint Committee for Guides in Metrology (JCGM) [22]. The most important international organisations for standardisation and metrology are members of the JCGM. The JCGM is chaired by the Director of the Bureau International des Poids et Mesures (BIPM), the highest authority in international metrology. Hence, the GUM is of the highest international metrological recognition and importance. Thanks to its general way of presentation, the methodology described can be applied to any field of metrology and ensures uniformity and comparability of measurement uncertainties. The GUM was first published in 1995. Since then, it has become internationally established and is used in all National Metrology Institutes. Furthermore, it also depicts the requirements of the DAkkS regarding the uncertainty of measurement for the accreditation of calibration laboratories and is mentioned in many standards and calibration guidelines.

The basic concept of the GUM is based on frequentist statistics. In principle, the true value of an *indirect measured variable* Y *is* unknown. The input quantities or *direct measured variables* X_1 , ..., X_n are regarded as random quantities. The measurement is modelled as a functional relationship

$$Y = f(X_1, \ldots, X_n)$$

Establishing this model is the first and, at the same time, possibly the most important or even most difficult step in the determination of the measurement uncertainty. The classical GUM method then describes a calculation by which the uncertainty of the indirect measured quantity Y can be calculated from the uncertainties of the input quantities X_1 , ..., X_n . This calculation is based on the error propagation method already described by C. F. Gauss, extended by taking into account the unknown systematic measurement errors which are treated by GUM on the same basis as the random measurement deviations.
Moreover, the GUM describes two methods for the determination of uncertainties

- Type A: Statistical analysis of series of observations carried out, if possible, under the same measurement conditions
- Type B Determination of the uncertainty by means other than statistical analysis of repeated measurements (for example from calibration certificates, manuals, sensor data, ambient conditions, ...)

The purpose of this distinction is merely to classify the uncertainty components according to their method of determination. Both methods are based on probability distributions. The uncertainty components obtained by using these methods are determined by calculating the standard deviation.

The scheme behind using the classical GUM method is that it is comparatively easy to implement and provides approximately correct results for a large class of measurement situations, as well as the possibility of easily adapting the result once it has been obtained or updating it with new measurement results.

This method, however, soon reaches its limits. It is basically an approximation method based on the linearisation of the model function f. If the model is not linear from the beginning, this approximation may already yield invalid results. Further problems arise if the input quantities do not have a symmetrical distribution or if individual quantities dominate over others. The classical GUM method is based on the propagation of standard uncertainties. The additional information from the distributions of the input quantities gets lost in the process.

To address these shortcomings, in 2008 the JCGM published an addendum to the GUM: *Supplement 1* (GUM-S1, [23]) describes the calculation of uncertainties based on the Monte Carlo Method (MCM). In contrast to the classical GUM method, the MCM is based on the propagation of probability distributions. The information from the distributions of the input quantities is fully taken into account. Moreover, there are far fewer conditions to be fulfilled for the application of the MCM than is the case with the classical GUM method. The distinction between Type A and Type B methods regarding the determination of uncertainties does not apply to the MCM. All input quantities are treated in the same way according to their underlying distributions.
The document *An introduction to the "GUM" and related documents* [24], published by the JCGM in 2009, explains the differences and similarities of the two methods very impressively. As a third method for the determination of uncertainties, it mentions the analytical method, in which the distribution of the measurand Y is directly determined through mathematical analysis. However, this is only possible in very simple cases. In order to compare these three methods in terms of their accuracy, [24] specifically states that the classical GUM method basically only provides an approximate solution, the analytical method is always exact (but only rarely applicable) and the MCM provides a solution with an adjustable numerical accuracy.

All three methods are suitable for establishing an uncertainty budget in addition to the actual result, the uncertainty of the indirect measurand Y. This uncertainty budget enables the analysis of the individual uncertainty contributions according to their respective influence on the overall result. Therefore, it is an important tool when the measurement process is to be examined for improvements.

For the sake of completeness, it should be mentioned that another concept for calculating uncertainties does exist. So far, this concept has not been considered by the GUM or its supplements. It is based on Bayes' theorem [25] and therefore follows a principle which fundamentally differs from that of frequentist statistics, which so far form the basis of the GUM. Revision of the GUM with a view to the integration of Bayesian statistics is a subject of current research [26].

The ISO 15530 series of standards [27], [28], [29] describes the most important methods for determining the measurement uncertainty in coordinate metrology. The methods dealt with are based on the approaches presented in the GUM (see 3.1.1). In some cases, however, they also go beyond that. For example, Part 2 of the series, which is currently being worked on, will deal with the description of a method based on multi-layer measurements. The work has been coordinated within a European research project [30].

With conventional methods, a task-specific determination of the measurement uncertainty for measurements on coordinate measuring machines can usually only be carried out with a great deal of effort. Often, the classic GUM method can no longer be carried out economically in an industrial environment due to the large number and complexity of the uncertainty influences and because it also requires a high level of expert knowledge. And what's more, in connection with the disadvantages described above, its application is not accurate enough for coordinate metrology in many cases.

A proven strategy, especially for demanding geometries, is the experimental determination of measurement uncertainty described in ISO 15530-3 using substitution standards. For each measurement task, this strategy requires a substitution standard whose size and geometry are comparable to the size and geometry of the measured object. Moreover, the measurement of the substitution standard and the measured object must be carried out with the same method and under comparable ambient conditions. The similarity between the substitution standard and the measured object is considered to be guaranteed if the dimensions of the two objects do not differ by more than 10 % and the angles do not differ by more than 5° [28].

The method for determining the measurement uncertainty then consists of a series of measurements on both the substitution standard and the measured object. The differences between the results on both objects enter into the calculation of the measurement uncertainty. The substitution standard used should be calibrated with a standard measurement uncertainty u_{cal} being as low as possible, since this value typically represents a significant portion of the total measurement uncertainty determined according to this method. **Moreover, the calibration of the substitution standard must have been carried out outside the own laboratory to be able to eliminate systematic influences from the measurement process used and to exclude correlations.**

The individual contributions to the measurement uncertainty according to this method are:

u_{cal}	Standard measurement uncertainty from the calibration certificate of the substitution standard
u_{p}	Standard measurement uncertainty of the measuring process
u_{b}	Standard measurement uncertainty from the systematic deviation between the results on the measured object and the substitution standard
u_{w}	Standard measurement uncertainty attributed to the deviations of the material properties between the measured object and the substitution standard

The expanded uncertainty $U\,(k = 2)$ is then calculated from these contributions according to

$$U(k = 2) = 2\sqrt{u_{\mathrm{cal}}^2 + u_{\mathrm{p}}^2 + u_{\mathrm{b}}^2 + u_{\mathrm{w}}^2}\,.$$

The following table shows a (possibly incomplete) overview of the influence quantities for the individual measurement uncertainty components.

Influence quantity	Method of determination (GUM)	Designation
Geometrical deviations of the measuring instrument Temperature of the measuring instrument Drift of the measuring instrument Temperature of the measured object Probing error (systematic) Probing error (random) Repeatability of the measuring instrument Scale resolution of the measuring instrument Temperature gradients in the measuring instrument Errors due to probe change Errors due to clamping, handling Errors due to contamination Errors due to measuring strategy	Type A	u_{p}
Calibration uncertainty of the substitution standard	Type B	u_{cal}
All influences from u_{p} and measurement environment during measurement of the substitution standard	Type B	u_{b}
Differences between substitution standard and measured object regarding • form • roughness • thermal expansion coefficient • elasticity	Type A or B	u_{w}

6 Traceability and standards

6.1 General

As part of the national quality infrastructure, traceability is an important concept, especially in the field of accreditation. As part of the national quality infrastructure, traceability is an important concept, especially in the field of accreditation. Therefore, an unbroken and traceable chain of measurements must guarantee the traceability to national standards, which in turn are linked to the International System of Units (SI) by primary measurement procedures. To this effect, the German Accreditation Body (DAkkS) has published an information sheet on metrological traceability within the scope of accreditation procedures (*Merkblatt zur metrologischen Rückführung im Rahmen von Akkreditierungsverfahren*) [31]. According to this, the measuring instruments and accessories used to calibrate the test specimens or to calibrate the measuring instrument must have a calibration certificate from a National Metrology Institute or a calibration laboratory bearing the accreditation symbol. The accreditation symbol demonstrates the competence of the calibration laboratory. Calibration certificates of foreign calibration bodies are also recognised, provided that these bodies are signatories of the Multilateral Agreement of the EA (European co-operation for Accreditation) or the ILAC (International Laboratory Accreditation Cooperation) for calibrations. It must be noted that each time the unit is passed on, there is a loss of accuracy characterised by an

increasing uncertainty of measurement, from the National Metrology Institute via the working standard used in industry to the product (see also calibration pyramid in Figure 1).
A recommendation regarding recalibration intervals of the standards and measuring instruments described in the following sections can be found in chapter 6.5.

6.2 Calibration aids

Auxiliary equipment for the calibration of threads includes, for example, measuring wires and double ball probes as well as gauges that are used to adjust the length measuring devices. The main items for calibrating length measuring instruments are gauge blocks serving as high-precision length standards, as well as setting mandrels and rings, but also test pins. However, these standards are inadequate for measurements performed in two-flank positions, as is typically the case in thread measurements. Instead, special gap standards or calibrated thread gauges are to be preferred.

6.2.1 Traceability of thread measuring wires

To establish traceability of the thread measuring wires, the guideline VDI/VDE/DGQ 2618 Part 4.2 is to be applied [32]. This guideline describes the measurands diameter, roundness, and parallelism by means of three options. For measuring wires with a diameter up to 1 mm, the calibration of the diameter and the roundness according to option 2 of the guideline is recommended. For these small diameters, the calibration of the parallelism is difficult to realise and is therefore not recommended. Besides, this diameter range has not been accredited so far. The form deviations have a direct effect on the pitch diameter with a factor of 3 (see also chapter 5) and must therefore also be taken into account in the measurement uncertainty budget. The additional calibration of the parallelism (option 3) is recommended for diameters of 1 mm and greater. These calibrations can be carried out by accredited laboratories. This option complements the calibration of diameter and shape in a useful way.

6.2.2 Traceability of double ball probes

There is no separate guideline that defines the way of how to establish metrological traceability of double ball probes. Therefore, the following paragraph describes in more detail the calibration and measurement of the double ball probes, which are mainly used for measurement with two-flank contact in internal threads.

For thread measurement, an application-oriented ball calibration in the planes of interest and areas of the contact points in the thread gap is useful. Here, the exact position of the probing points on the probe balls depends on the thread profile angle of the gauges to be calibrated and the positioning of the double ball probe. Since there are many standard threads with different profile angles, it is advisable to cover as large an angle range as possible during calibration. The alignment is determined by the arrangement of the balls and often also by the mounting (holder) used. Furthermore, the position of the thread gauge (horizontal or vertical) must be taken into account. The contact points are then offset at an angle of 90° to the alignment of the probe balls of the double ball probe. The measuring points to be recorded on the probe balls must cover at least the range resulting from the thread profile angle of the intended measuring objects. Since the profile angles of the thread gauges and thus also the areas of interest on the balls vary, it is also possible to calibrate the complete sphere. A concrete recommendation is described in [21]. Figure 15 shows an example of the contact points (point pattern) of a ball calibration for measuring metric threads. In an angular range of ± 10° around the profile angle, which defines the contact points of the probe balls, two additional circles are measured above and below the profile angle. The calibration of the probe balls is often carried out with universal 3D coordinate measuring machines. These measuring devices can be individually programmed to meet the requirements. Meanwhile, there are several accredited calibration laboratories able to confirm the metrological traceability. These laboratories have also been specifically accredited for double ball probes as calibration objects.

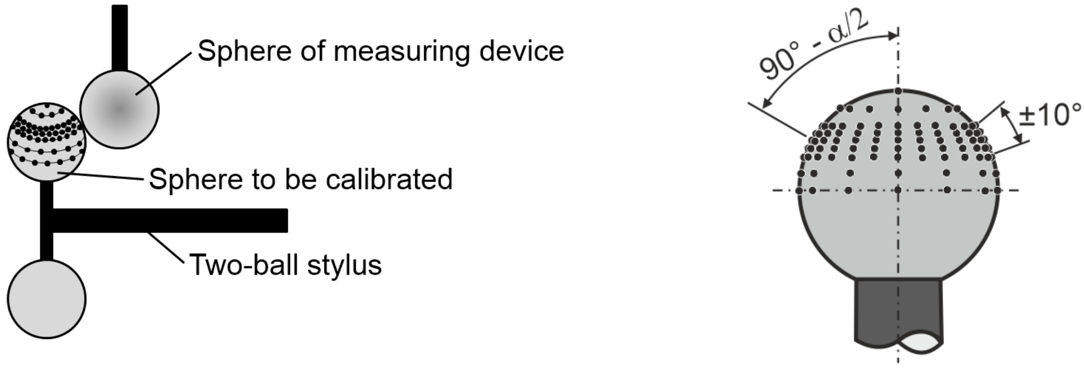

Figure 15: Pattern (calibration points) for calibrating screw thread probe balls

Moreover, so-called gap standards can be used to determine the stylus constants of two-ball styli. The advantage of this measuring method is that the conditions at or at least near the actual contact points of the thread flanks are taken into account. Moreover, the probe bending, and the probing force are included in the measurement result, providing a very good representation of the self-centering probing in the thread groove.

The gap standard consists of at least two adjacent calibrated precision spheres arranged on a thermally invariant base plate in such a way that they represent one or two gaps. Figure 16 shows a possible configuration of the gap measurement standard.

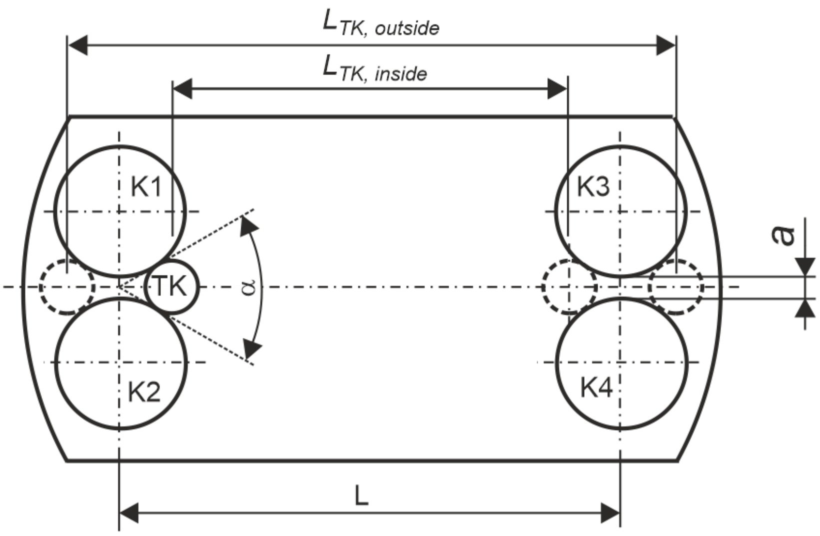

Figure 16: Schematic representation of the principle of the gap measurement standard

Here the balls K1 and K2 as well as the balls K3 and K4 each form two gaps. The length to be measured $L_{\mathrm{TK,\,inside}}$ or $L_{\mathrm{TK,\,outside}}$ results from the probe ball diameter d_{TK}, the ball diameters D and the ball distances a and L (Figure 16). The probe ball diameter d_{TK} and the ball distance a must be coordinated in such a way that probing takes place approximately at the angle α which also applies to the respective application. For metric threads this would be the thread profile angle α = 60°. The gap standard is designed according to equation (9) and Figure 16.

$$a = (D + d_{\mathrm{TK}}) \cdot \cos\left(\frac{\alpha}{2}\right) - D \quad (9)$$

To determine the lengths to be measured $L_{\mathrm{TK,\,inside}}$ or $L_{\mathrm{TK,\,outside}}$, the distances between the centre points of the precision spheres K1 to K4 are calibrated. Coordinate measuring machines are suitable for this purpose. Coordinate measuring machines with laser-based measuring systems can be used to increase accuracy. Six length measures are determined from the sphere centres by means of trilateration. An example of a gap measurement standard is shown in Figure 17. It has been designed for the most common thread pitches P from 1 mm to 6 mm.

Figure 17: Example of a gap measurement standard

Table 2 shows an example of the design of a gap standard for metric threads (α = 60°) for some thread pitches according to DIN 13-1. First, equation (1) is used to determine the optimum probe ball diameter d_0, which is then used as probe ball diameter d_{TK} in formula (9).

Table 2: Examples for different thread sizes

Thread pitch P in mm (according to DIN 13-1)	**Probe ball diameter d_{TK} in mm**	**Ball diameter D in mm**	**Distance a in mm**	**Probing angle α in °**
0,35 – 0,6	0,23 – 0,35	1	0,1	53 - 70
0,7 – 1,0	0,40 – 0,58	2	0,1	58 - 71
1,25 – 2,0	0,72 – 1,15	3	0,3	55 – 75
2,5 – 4,0	1,44 – 2,31	5	0,9	47 – 72
4,5 – 6,0	2,60 – 3,46	5	1,9	50 - 71

To use the standard for substitution, the similarity criterion must be fulfilled, see also chapter 7. This concerns not only the probing angle α but also the length to be measured $L_{\text{TK, inside}}$ or $L_{\text{TK, outside}}$ (Figure 16). This traceability option is discussed in more detail in chapter 7.

6.3 Traceability of the measuring devices for thread calibration

6.3.1 Length measuring instruments

To calibrate the simple pitch diameter, 1D length measuring devices are frequently used. The traceability of these devices is often provided by external, accredited suppliers (see also chapter 4.1 To establish traceability, specific standards and guidelines are available, such as ISO 10360-2 and -5 as well as VDI 2618 Part 17.1 (Test instruction for horizontal length measuring machines) [33][34][35]. That is why this article does not give a detailed description on how to establish the traceability of length measuring devices. Nevertheless, a calibration or zeroing of the measuring system must usually be performed before carrying out the thread measurement. For this purpose, cylindrical gauges such as cylindrical measuring pins, plug gauges and plug rings, as well as gauge blocks, which generally have a lower measurement uncertainty, can be used. When using plug gauges and plug rings, it must be ensured that they are either fully calibrated in diameter, shape, and parallelism, or that their calibrated axes are marked. In the latter case, it is sufficient to calibrate the diameter, as the reproducibility of the diameter calibration is given by the markings on the gauges.

Another possibility for a traceable thread calibration consists in using the measuring instrument as comparator by means of a substitution measurement with a traceable thread gauge. In this case, it is necessary to observe the principle of similarity (see chapter 7).

6.3.2 Contour measuring devices

Contour measuring devices are used for the method described in chapter 4.2. Contour measuring devices are scanning 2D measuring devices whose measuring principle (also called tactile stylus method) is based on scanning the surface of the measured object linearly in the axial and radial direction of the object to be measured (see also VDI/VDE 2629 Part 1 [36]). Due to the axial feed in connection with the radial scanning of the contour, the measuring forces, the sliding friction, and the resulting forces on probe and measuring system play a major role in this measuring technique. The resulting bending effect needs to be compensated. Therefore, the traceability is realised via geometrically similar standards, see also VDI/VDE 2629 Part 2 [37]. Essentially, optical flats, contour standards and precision spheres as well as special standards for calibrating the probing system are used for this purpose. However, [37] does not describe how to realise traceability to the diameter. Here, plain gauges such as plug gauges and plug rings would be suitable. Plane face glass plates are used to assess straightness deviations. Contour standards represent two-dimensional regular geometries such as straight lines and circles and allow the shape, angle and length to be assessed. Plug gauges and plug rings are available in almost all dimensions and can therefore be used for substitution for diameter measurands. To ensure that the principle of substitution is observed, the diameter of the substitution standard should not deviate by more than 10 % from the diameter of the test specimen. More details are described in ISO 15530-3 [28]. The probe systems consist of a “needle” with a probe tip at each end, the tips of which are used for roughness measurement down to a radius of 2 µm, depending on the application. The tips of the probes are round or flattened, depending on the application. The calibration is device-specific, using special calibration standards or precision spheres.

6.3.3 Three-dimensional coordinate measuring machines

At present, three-dimensional coordinate measuring machines are still very rarely used in screw thread metrology (see chapter 4.3). Generally, their purchase and maintenance costs are very high. Nevertheless, due to their wide range of applications, these measuring devices offer the best prerequisites for holistic measurement of thread geometry. Ultimately, the goal of a thread calibration should be the areal measurement and evaluation of the screw surface, because this is the best way to assess the mating ability. For thread measurement, the CMM should be equipped with a rotary table. The traceability of the coordinate measuring machines is also relatively complex. To fully account for the kinematics of a CMM with three Cartesian axes, a total of 21 components of geometry deviations must be determined based on a rigid-body model and then corrected mathematically [38]. Additionally, the deviations of the rotary table must be taken into account. The geometry deviations are measured by means of step gauge blocks, Zerodur hole plates, spherical plates, spherical standards, or interferometric measuring systems (for example, laser tracers). A correction field is then calculated from the measurement results, assigning a correction value to the CMM at every point within the measurement volume with the help of the software. Despite this complex procedure, residual errors remain. These are indicated in the measurement uncertainty or in the specification of the machine. Calibrated reference spheres (precision spheres) are used to calibrate the probe system. This is done to determine the position of the probing elements in the measuring volume. To be able to determine this position as accurately as possible, a reference sphere and an additional reference probe are required, both of which should only show minimal deviations in shape. The reference sphere must also be calibrated in diameter. The reference probe is used to calibrate the reference sphere according to a routine stored in the software in order to determine its centre point coordinates. The probe system is then calibrated. In this procedure, all probe balls of the probe system are calibrated by means of a mostly predefined routine and thus the position in the measuring volume as well as the diameter of the probe elements are determined. Depending on the diameter of the probe elements, it may be necessary to use several reference spheres with different diameters. When using a rotary table, the axis of the rotary table must be determined using a suitable method. Usually, this is done using the one-ball or two-ball method. By measuring the sphere or both spheres in selected positions, the position and orientation of the axis is determined. The procedures for checking the accuracy of coordinate measuring machines are described in detail in the ISO 10360 series of standards as well as in the VDI 2617 series of guidelines.

6.4 Task-specific traceability by means of substitution standards

The screw surface of a thread is a metrologically demanding geometry. The probing points in two-flank contact are not located in the same axial section of the thread, and the contact point of the probe balls on the thread flank is hardly taken into account when calibrating the probe. In contrast to regular geometries, like those of plug gauges and plug rings or gauge blocks, the probing points are generally not located at the pole or equator of the probe ball. Other influencing factors to be considered are the probing conditions, especially when measuring with double ball probes in self-centering mode to determine the lead or pitch and the indicated value for the pitch diameter. Ideally, there should be equal distribution of the probing force on both flank surfaces, but in practice this is difficult to achieve.

To ensure a practice and application-oriented traceability and to take into account the thread-specific features mentioned above, standards similar to the workpiece are used. This method considers the above-mentioned influences while also checking the complete measurement chain from the measurement of the probe to the calculation of the measurement result.

The principle of a substitution is based on the use of standards (in this case thread gauges) which ideally represent the same geometrical parameters as the test specimen. A good mapping of the ideal geometry and only minor deviations in dimensions and shape are also advantageous. In this case, the influences from differences of the ball or wire diameter used from the ideal value are negligible. The standard must be very well known, which means that it must be calibrated in all parameters with correspondingly small measurement uncertainties for the respective applications. If the geometry parameters of the standard deviate from the geometry parameters of the test specimen by up to max. 10 %, this can be referred to as a substitution standard. If the deviations are greater, they must be taken into account in the measurement uncertainty. The calculation of the measurement uncertainty for substitution measurements is described at the end of section 5.2 of this report.

6.5 Recommendations for recalibration intervals of reference standards and auxiliary equipment

Reference standard / auxiliary equipment	Recommended recalibration interval	Remark
Measuring wires	1 to 3 years	depending on use; possibility of intermediate inspection
Double ball probe	1 to 3 years	depending on use; possibility of intermediate inspection
Gauge blocks	max. 3 years	if history is available
Ring gauges and plug gauges	max. 3 years	if history is available
Cylindrical measuring pins	1 to 3 years	depending on use; possibility of intermediate inspection
Optical flats	none	check for damage of the surface
Length comparator	1 year	depending on the frequency of use, an intermediate inspection is required
Contour measuring device	1 year	depending on the frequency of use, an intermediate inspection is required
3D Coordinate Measuring Machine	2 years	with intermediate inspections
Substitution standards (thread plug gauges and ring gauges)	1 to 3 years	if history is available
Gap measurement standards	1 to 3 years	

7 List of measures to be taken by calibration laboratories

The following is a summary of the most important measures to be taken to ensure successful calibration of thread gauges.

The measurement results from the measurements in this table must always be analysed. This means that they must be recorded and statistically evaluated to detect any changes. If necessary, immediate action has to be taken.

Time interval	Measure	Remark
3 to 5 years	**Proficiency testing / Comparison measurement** of thread gauges with other accredited calibration laboratories	organised by DKD's Technical Committee *Length*, external service providers or own organisation
3 years	**External calibration of the working standards** by an accredited calibration laboratory or PTB (or another NMI): • gauge blocks as well as smooth ring gauges and plug gauges used for establishing traceability of the measuring devices • thread gauges used as substitution standards according to ISO 15530-3 in thread calibration	see chapters 6.3 and 6.4
Annually	**Calibration of the measuring devices used** according to currently valid standards and guidelines	see chapter 6.3
	Intermediate verification of the measuring device to ensure correct functioning of the measuring device	Requirements from DIN EN ISO/IEC 17025:2018, stated in sections 6.4.1 and 7.7 of the guideline
	Calibration of measuring wires according to VDI/VDE/DGQ 2618 Part 4.2 Option 3	see chapter 6.2
	Calibration of double ball probes (no standard or guideline available) incl. diameter and form measurement, optical inspection of ball surface	see chapter 6.2
	Calibration of the temperature measuring systems in the measuring rooms and at the calibration stations or measuring devices with at least three measuring points in a temperature range from 18 °C to 22 °C	see chapter 6.2

	Recalibration of the laboratory's own gauges • with different procedures or measuring instruments and aids • with different staff under the same conditions (measurement methods and measuring device)	requirements from DIN EN ISO/IEC 17025:2018, stated in section 7.7 of the guideline annually, or when necessary – might be necessary several times a year
Annually, or after analysis of the measurement results	**Deriving measures** from the measurement results (training, repeated comparison measurements, repairs, software updates, additions/changes to the work instructions), incl. monitoring the success of the actions taken	requirements of DIN EN ISO/IEC 17025:2018, stated in section 7.7 of the guideline
With every calibration of threads	**Use of traceable working standards** • Thread gauges for calibration according to the substitution method in accordance with ISO 15530-3 [28] which fulfil the similarity principle. This means that the geometric parameters of the test specimen deviate by max. 10 % from those of the substitution standard. • Calibrated gauge blocks, smooth ring gauges rings or plug gauges can be used for substitution of core diameters (for internal threads) or major diameter (for external threads).	see chapter 6
Permanent	**Keeping a stock of calibrated thread gauges** (from complete geometry measurement according to section 4.5) for internal and external threads with good quality of the gauges (small deviations in dimension and shape), available in different dimensions. They should be adapted to the scope of accreditation and cover as wide a range of components as possible.	requirements from DIN EN ISO/IEC 17025:2018, stated in section 7.7 of the guideline

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