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Quality Management in the Automotive Industry

Inspection Process Management for Static Torques on Bolted Joints

2nd revised edition, February 2024

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Qualitäts Management Center (QMC)
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Note on gender

For reasons of readability, the masculine form is used throughout this text. However, all information applies to both genders.

Preface

The measurement of static torques on bolted joints is subject to various influences. Interpreting the measurement results in terms of their accuracy – if that word even applies – is not always easy.

A major challenge, and a prerequisite for making statements regarding quality, is generating reproducible and measurable characteristics.

Inspection process capability is covered in this VDA Volume 5.2. Readers are given a “recipe” for torque-based inspection processes, enabling them to select the ideal measuring method for their specific bolted joint characteristics (irrespective of whether a torque-controlled or torque angle-controlled procedure is used).

Table of Contents

1 Standards and guidelines

Bolted joints are of vital importance in the automotive industry, since they are frequently used (more than 100 million threaded fasteners are tightened in German automotive companies per working day).

When it comes to producing bolted joints, a distinction can be made between the actual production process and an inspection process carried that follows the production process. The production process is carried out using suitable tools selected according to tightening specifications. This volume only covers the inspection process that is conducted after the production process. Some of the tightening tools include integrated functions that serve to monitor the process sequence. However, these monitoring functions are not covered in this VDA volume.

The most frequently used type of inspection is based on determining static torques in order to use them as an auxiliary quantity for the actually relevant preload. Due to the complex relationship between preload and torque (see Chapter 3.1), the quality of the “torque” characteristic is not comparable to the quality of characteristics that can be measured directly. Moreover, multiple measurements of this characteristic on the same object, which are actually common practice in order to quantify inspection process capability, are not possible when it comes to bolted joints. Any tightening or loosening changes the condition of the measured object irreversibly.

In this volume, the approach presented in VDA Volume 5 [1] is therefore modified in such a way that it can be applied to bolted joints.

The following recommendation of how to handle measurement process capability in case of torque inspections on bolted joints is based on practical experience. The purpose of this recommendation is to reduce the required efforts to an adequate degree.

The examples described in this volume help to illustrate relevant aspects. The notations used might differ from specifications provided by manufacturers of measuring and inspection equipment.

2 Use and Scope of Application

The objective of this volume is to present an approach to validating inspection process capability for static torques in order to achieve a realistic statement regarding the bolted joint produced.

Further inspection methods for bolted joints that cannot be further tightened or are not suitable for evaluation are covered in chapter 5.

3 Terms and definitions

The definitions of terms pertaining to inspection process capability are provided in VDA Volume 5 [1]. The present volume is based on the latter and merely adds definitions of specific terms related to bolted joints.

In contrast to VDA Volume 5 [1], VDA Volume 5.2 uses a reference instead of a reference standard.

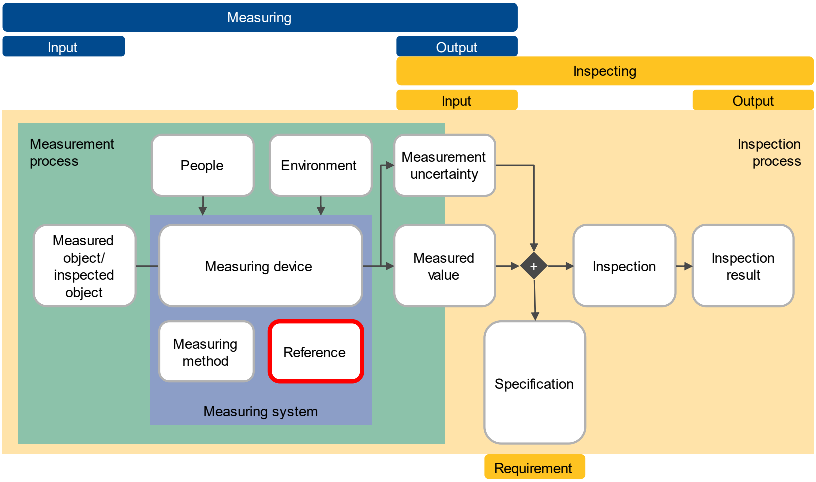


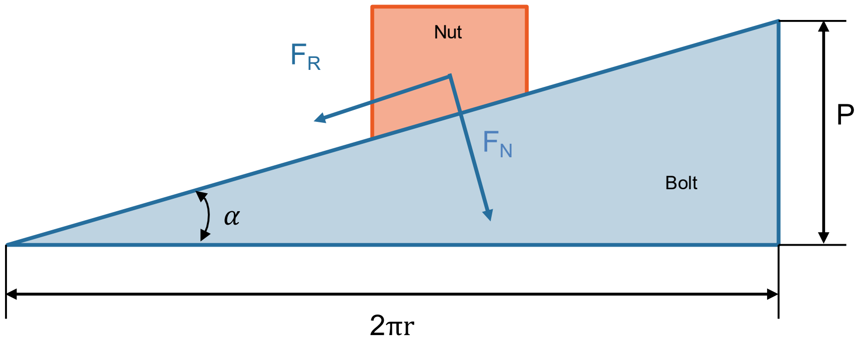
Figure 3-1: Relationship between measuring system, measurement process and inspection process based on VIM and ISO 3534 [9, 10], with respect to VDA Volume 5.2

3.1 Mechanical Relationships in the Bolted Assembly

3.1.1 Fundamentals

Bolted joints are a combination of a bolt and a nut or a male set screw (bolt) and a female component (nut). The positive locking effect between the threads of the bolt and the nut determines the effectiveness of the bolted joint.

In unwound condition, the thread corresponds to an inclined plane (seeFigure 3-2). A rotation of the bolt relative to the nut causes the thread flanks of the bolt to slide across the thread flanks of the nut and thus generates a linear motion (operating principle).



P = Thread pitch, α = Pitch angle
F_R= Friction force, F_N= Normal force

Figure 3-2: operating principle of a thread

Figure 3-3illustrates a simplified model of a bolted assembly. The bolt can be regarded as a pull-spring that elongates once a torque is applied. The clamped parts are represented by compression springs compressed as a function of the applied preload, respectively the acting surface pressure and material properties.

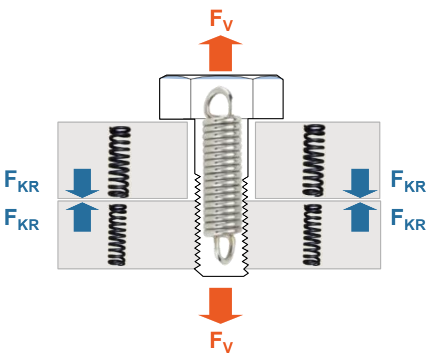


Figure 3-3: Simplified model of a bolted assembly

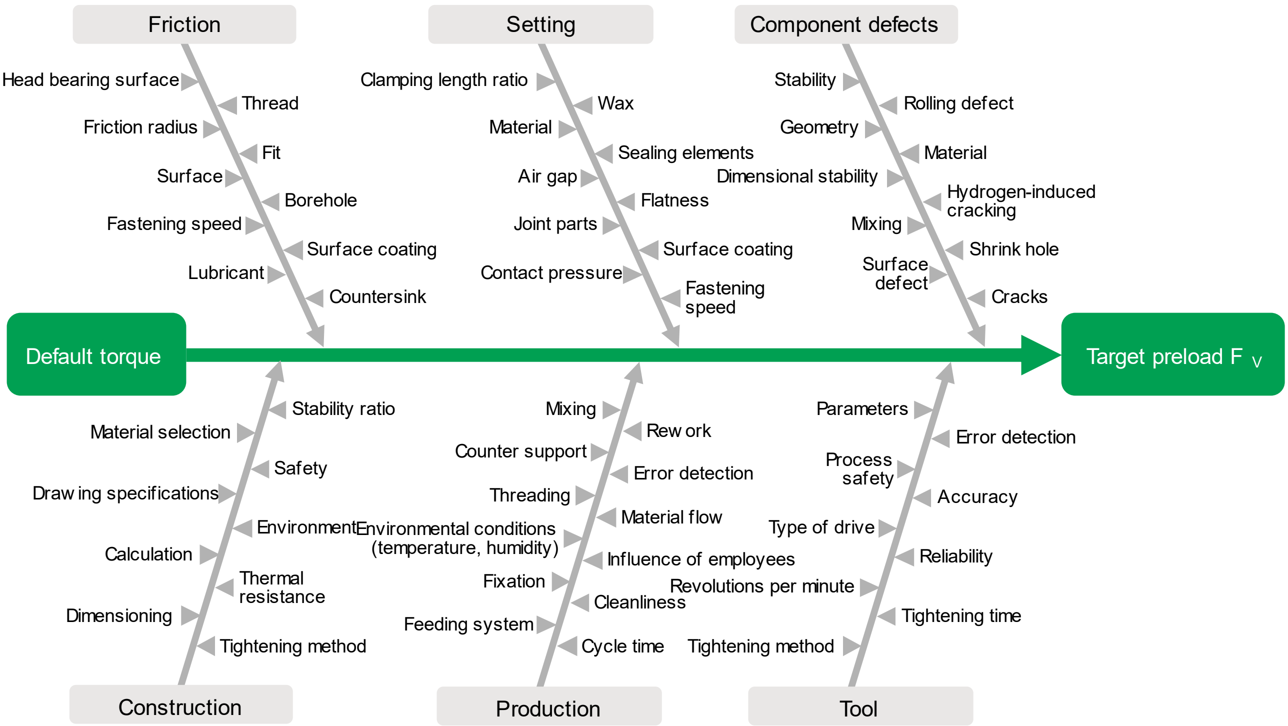


Figure 3-4: Influencing factors affecting the preload created during torque tightening

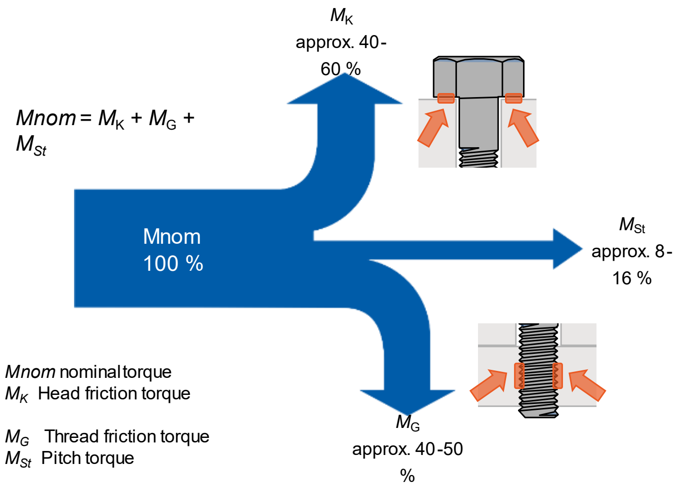


Figure 3-5: Basic torque partitioning

The nominal torque M_{noml} applied to create preload is composed of the head friction torque M_K, the thread friction torque M_G and the pitch torque M_{St} that actually generates preload (see Figure 3-5). The formula specifying the relation between the applied nominal torque M_{nom} and the achieved assembly preload F_M for metric screw threads according to ISO 68-1 [3] is as follows (see VDI 2230 [2]):

$$M_{noml} = F_M \left(0.16 \times P + 0.58 \times d_2 \times \mu_G + \frac{D_{Km}}{2} \times \mu_K\right)$$

where:

M_{nom}	Nominal torque (in $N \cdot m$)
F_M	Assembly preload (in N or kN)
P	Thread pitch (in mm)
d_2	Pitch diameter (in mm)
μ_G	Coefficient of friction in the thread (non-dimensional)
D_{Km}	Effective diameter for the friction torque in the bolt head or nut bearing area (in mm)
μ_K	Coefficient of friction in the head bearing area (non-dimensional)

The coefficient of friction in the bolt head or
nut bearing area and of the friction in the $\mu_K$thread μ_G in the formula are a measure for the lubrication condition of the surfaces in contact moved during assembly.

As Figure 3-5 illustrates, a significant part of the applied tightening torque is absorbed by the friction between the head and the head bearing surface as well as by the friction in the thread. Ultimately, only 8 to 16 % of the applied tightening torque develops the preload holding the components together. Thus, it is not possible to draw conclusions on the achieved preload based on torque only.

In order to assess the achieved assembly preloads in a bolted joint by means of the tightening torque,
the coefficients of friction are kept constant within defined limits (see VDA 235-101 [4]) by coating threaded fasteners with specific lubricants. However, this means that the assembly preload of a bolted joint cannot be predicted in the form of a specific value, but only in the form of an expected range. In practice, this range is additionally influenced by e.g. altered surface conditions of the components as well as by environmental aspects (see Figure 3-4 on the respective influences).

The tightening factor α_A expresses the relation between the minimum and maximum assembly preload:

$$\alpha_A = \frac{F_{Mmax}}{F_{Mmin}}$$

For torque-controlled tightening α_A, the tightening factor is usually around 2.

3.1.2 Preload and Torque

If a torque is applied to a bolted joint, the thread pitch of the bolt and the nut translates the rotary movement into a linear movement. The bolt is elongated in the process, while the remaining parts are compressed (see Figure 3-3).
Due to the friction on the underhead and the thread, only a limited part of the originally applied torque is available in order to elongate the bolt according to Hooke's law.
The preload can only be measured by means of the changes in length of the bolt, which is difficult to do under series production conditions. Given that the torque is proportional to the generated preload under constant friction conditions, statements can me made regarding the achieved ratio between the required target values for a bolted joint, i.e. the applied torque

and the static torque. It must be taken into account that the static torque was applied and documented in relation to the actual target quantity (clamping force / preload). Helpful methods include bolted joint analyses and the determination of the tensile yield point.

3.2 Torque Terminology

Fastening speed
Refers to the entire tightening process of a bolted joint. The latter can be subdivided into several speed / speed ramp ranges. The fastening speed influences the assembly result and the inspection result of the process capability inspection.

Note: In contrast to the terminology used in ISO 22514 and in VDA Volume 4, this volume uses the VDI term process capability instead of process performance.

Tightening specifications
Specification of tightening parameters for a bolted joint, e.g. nominal torque, snug torque, tolerance specifications, fastening speed, tightening methods, assembly sequence, insert direction, application of force, etc.

Examples of tightening torque $\boldsymbol{M_A}$:

10 $N \cdot m$ ± 1,5 $N \cdot m$	10 $N \cdot m$ ± 15 %
10 $N \cdot m$ (nominal torque)	10 $N \cdot m$ (nominal torque)
±1.5 $N \cdot m$ (tolerance)	± 15 % (tolerance)

Examples of **torque angle-controlled tightening:**

$(50N \cdot m \pm 7.5N \cdot m) + (90° \pm 15°)$	$(50N \cdot m \pm 15\ \%) + (90° \pm 15°)$
50 $N \cdot m$ (snug torque)	50 $N \cdot m$ (snug torque)
±7.5 $N \cdot m$ (tolerance)	± 15 % (tolerance)
90° (target anglel)	90° (target angle)
±15° (tolerance)	±15° (tolerance)

Attributive torque inspection (minimum torque inspection)
Attributive torque inspection is performed by applying an inspection torque (typically nominal torque) in tightening direction.
The bolted assembly is deemed to be "OK" if the fastener does not rotate further. This inspection proves that the bolted joint has been tightened.

Loosen/untighten
Rotating the driven fastener against tightening direction.

Breakaway torque M_{LH}/M_{WH}
The breakaway torque in loosening direction M_{LH} and during further tightening M_{WH} is the torque required to overcome the static friction in order to rotate the fastener in tightening direction after initial installation of the joint (see Figure 3-6).

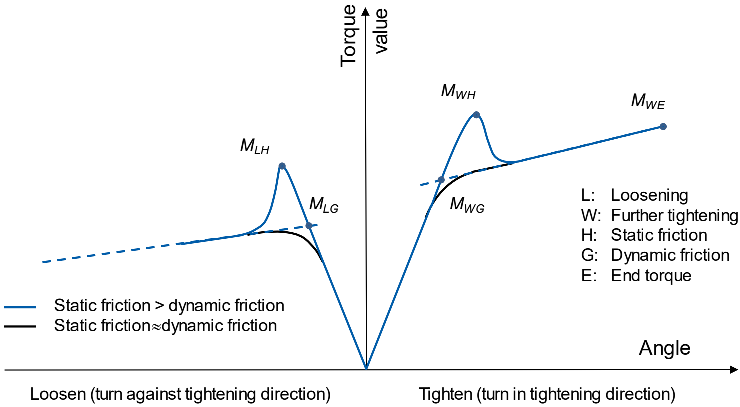


Figure 3-6: Schematic torque-angle diagram in loosening and tightening direction of an installed bolted joint.

Bolted joint analysis (for static torques)
In order to determine inspection process capability in accordance with VDA Volume 5.2, it is necessary to be familiar with the characteristics of the relevant bolted joint. An appropriate evaluation method can be determined by means of analysing the torque-angle curves as described in chapter 6.2.

Bolted assembly / bolted connection [15]
Threaded connection that can be loosened and that joins two or more parts together.

Note 1: It can include one or more bolt locations / bolted joints.

Note 2: Refers to bolts as well as other components with threads (e.g. lids, union nuts, adjusting screws or adjusting nuts)

Note 3: Constructional requirements can be that the connected parts must behave like one single part under all operating forces that occur, that electrical contacting is ensured, that the parts are fixed in position, etc.

Note 4: For differentiation, see bolted connection, bolted joint, bolt location

Nominal torque M_{nom}
Target value for the torque
.

Further Tightening
Rotating the driven fastener of the pre-loaded joint in tightening direction.

Static torque M_{WG}
The static torque is the torque required to further rotate the fastener at the respective bolt location in tightening direction.

3.3 Tolerance limits of the static torque

Experience has shown that due to the vast number of influencing factors (see Figure 3-4), the upper and lower tolerance limits for the nominal torque defined in the tightening specifications can often not be used as inspection limits (e.g. for the static torque). Therefore, different approaches have been established in order to specify inspection limits. They are based on experience, general default values, back calculation based on recorded values or on a combination of these approaches (e.g. general default values for preproduction and start of the series, back calculation during series production, see VDI/VDE 2645-3 [13], Chapter 9). The objective of specifying inspection limits in this manner is to reliably detect errors and to avoid false alarms, i.e. assessing a condition as NOK even though it is OK.

The defined inspection limits can differ for the same bolted joints produced under different boundary conditions (e.g. production in an air-conditioned/not air-conditioned environment, manual/automated production).

In some cases, it might be necessary to adjust the defined inspection limits at a later point in time due to changes in the influencing factors or on the basis of actual measurement results.

3.4 Differentiation between tool and measuring equipment

A tool is defined as a device which applies a torque to a threaded fastener (e.g. to a bolt) in the context of an assembly process. The capability of a tool is evaluated e.g. in the form of a short-term/machine performance study (also referred to as a machine capability study).

Measuring equipment is defined as a system which applies a torque to a threaded fastener (e.g. to a bolt) for measurement purposes in order to determine the static torque (see Figure 3-1). The methods for determining inspection process capability are covered in this VDA volume.

4 Inspection process management

When it comes to the structure of the individual sub-processes, inspection process management for bolted joints does not differ from the approach described in VDA Volume 5 [1]. Inspection process management therefore comprises risk-based assurance, the complaints process, proof of efficiency, and the safeguarding of inspection results, taking measurement uncertainty into account. As described in VDA Volume 5, Chapter 4.1.2 [1], DIN EN ISO 14253-1 [8] must be applied here.

4.1 Roles and competences in inspection process management

Applies to bolted joints in the same way as described in VDA Volume 5 [1]. Additional roles and competences can be found in VDI/VDE MT 2637-1 [14].

4.2 Inspection process planning

Applies to bolted joints in the same way as described in VDA Volume 5 [1].

4.3 Risk-based assurance

The risk-based assurance of inspection process capability is a procedure for validating inspection decisions while also
factoring in economic requirements (see VDA Volume 5, Chapter 4.3. [1]). In addition to the requirements set out in VDA Volume 5 [1], which are based on the VDI guideline regarding inspection process management (VDI/VDE 2600 Part 1), the requirements set out in VDI/VDE 2862-1 [7] (A, B, C categorisation) must also be taken into account when it comes to bolting applications.

The following overview shows the connection between special characteristics relevant to safety, approval and function (see VDA process description of special characteristics, Chapter 3) and the categories from VDI/VDE 2862-1 [7] in bolting technology.

Inspection characteristics which are not special characteristics fall into category “C”. The white arrows indicate an “upgrade” to a higher level, whereas the black arrows indicate a definite allocation.

Table 4-1: Comparison between VDA special characteristics and VDI/VDE 2862-1 [7] categories

Characteristic	CC / SC S / SC A	SC / SC F
	Relation to the direct customer (OEM) AND/OR the end customer	
Definition	...are product characteristics or process parameters that are specified by the customer or by the organization and that can have a significant influence on the safety of the vehicle or the fulfilment of statutory requirements, the fit, the function, the performance or further processing of the product.	... are product or process characteristics that can either have a significant influence on the customer's satisfaction with the product in terms of assembly, function, installation or look, or can impact the ability to process of manufacture the product.

Category	Category A	Category B	Category C
Definition	A bolted joint/bolted connection is put into category A if the failure of this bolted joint/bolted connection is very likely to lead to the vehicle's failure in terms of safety or the destruction of the overall vehicle, and thus poses a danger to life and limb.	A bolted joint/bolted connection is put into category B if the failure of this bolted joint/bolted connection leads to malfunctions of the vehicle that make it impossible to independently reach the nearest service workshop, and if category A criteria are not met.	A bolted joint/bolted connection is put into category C if it is not in line with definitions of categories B or C.
	Relation to the end customer/user		

4.4 Inspection equipment management

Inspection equipment management for bolted joints is the same as described in VDA Volume 5 [1].

Note: In VDA 5.2, measuring system uncertainty is no determined based on repeat measurements on a calibrated standard, but rather on the basis of a calibrated reference (measuring brake). If a component is used as a reference, the usual measures in relation to inspection equipment management aren't applicable.

4.5 Proof of effectiveness of inspection process management

Applies to bolted joints in the same way as described in VDA Volume 5 [1].

4.6 Calibration

The requirements regarding calibration laboratories are described in VDA 5, chapter 4.5.2. Minimum calibration requirements are described in VDI/VDE 2645-1 [11]

5 General inspection and measurement processes

In series production, bolted joints can generally be inspected by means of torque-related or elongation-related procedures. Since inspection process capability based on elongation detection (e.g. time of flight measurement of ultrasonic waves, measurement of changes in length before and after bolt plastic deformation) can be assessed according to VDA Volume 5 [1], the following chapters cover only torque/angle-related inspection procedures. These inspections must be carried out within a defined time-frame after installation of the bolted joint and before dynamic and thermal loads are applied.

5.1 **Static torque** (torque for further tightening)

In this procedure, the bolt is further rotated in tightening direction, and a torque angle curve is generated. The evaluation of this curve is described in greater detail in chapter 6. When carrying out the inspection, it must be ensured that the joint isn't damaged as a result of the further tightening.

5.2 Loosening and Re-tightening (”back to mark“)

This procedure is only used for analysis purposes. Its use in series production monitoring is not permissible.

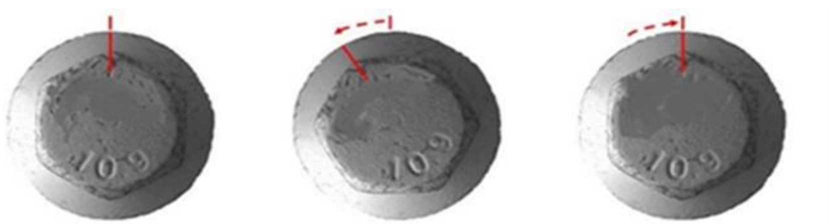


Figure 5-1: Principle of loosening and re-tightening

In the "back to mark" procedure, the fastener is loosened by a predefined angle (see Figure 5-1). The preload should not be reduced to "0". The bolted joint is then re-tightened until the initial position is reached again. The maximum torque recorded there represents the torque applied at the respective bolt location.

The disadvantage is that the available friction conditions change when the bolted joint is loosened, e.g. the loosening process carries off oil, which might falsify the inspection results.

5.3 Attributive inspection

The risks of attributive inspections are described in detail in VDA Volume 5 [1], Chapter 9.

In exceptional cases, an attributive inspection can make sense or can be necessary, e.g. in case of a bolted joint that must not be tightened further as it could otherwise be damaged, or in case of small / very large torques (e.g. < 3 $N \cdot m$; > 500 $N \cdot m$), or bolt locations that are not easily accessible.

When it comes to torques, a possible attributive inspection is the so-called minimum torque inspection. This entails applying a pre-defined inspection torque to the fastener in tightening direction. The inspection result is “OK” if the fastener does not rotate further. This inspection proves that the bolted joint has been tightened.

There are two different variants:

1. Minimum torque inspection with a mechanical torque wrench (break-over torque wrench).

   In this case, the inspection is carried out by means of a break-over torque wrench and a pre-defined torque that is applied to the fastener in tightening direction. The bolt must not rotate further. Whether a meaningful result can be achieved depends to a large extent on the employees’ qualification. In order to help detect further rotation, it is recommended to mark the initial position (see Figure 5-1).

2. Minimum torque inspection with electronic torque wrench and angle monitoring

   In oder to reduce the employees’ influence on the measurement uncertainty, it is recommended to carry out this inspection by means of an electronic torque wrench with angle monitoring.

Both variants have the disadvantage that it is not possible to detect whether an excessive assembly torque has been applied.

In addition to the inspection, the assembly can be safeguarded/secured by using mechanical torque wrenches (production equipment/tool). Proof can thus be obtained that the bolted joint has been tightened. This is useful in terms of process assurance during start-ups (for a limited period of time, until the static torque analysis has been carried out), small series or as an emergency strategy in case of system failures.

5.4 Loosening torque

An evaluation of the loosening torque M_{LG} is not permissible in series production inspection and is generally only used for analysis purposes. the ideal torque-angle curve shown inFigure 3-6 is difficult to prove in practice due to the overlap between the drop in preload and torque.

Note 1: The loosening torque is determined e.g. in order to evaluate the thermal loosening characteristics (see VDA 235-203 [5]).

Note 2: The loosening torque is only suitable to a limited extent when it comes to qualitative evaluations of bolted joints. This is because the measurement is carried out against the tightening direction, meaning that the prevailing forces are different from measurements in tightening direction (see Figure 3-6).

Note 3: This process is not permissible in series production monitoring, as no quantitative statements can be made on the applied preload.

Note 4: An evaluation of the breakaway torque M_{LH} is not permissible either.

Note 5: The loosening torque is also measured within the scope of verifying the effectiveness of the measures for securing the bolted joint.

6 Measurement and inspection process capability of bolted joints

6.1 Special influences in case of bolted joints

Bolted joints are characterised by the fact that the measured values for static torques are subject to very specific influences.

Since these influences impact the measurement process too significantly, a measuring brake should be used as a reference for inspection process capability (as described in chapter 8).

In case of stable bolted joints with minor influences, a component can be used.

The following Ishikawa diagram shows the relevant influences (see Figure 6-1).

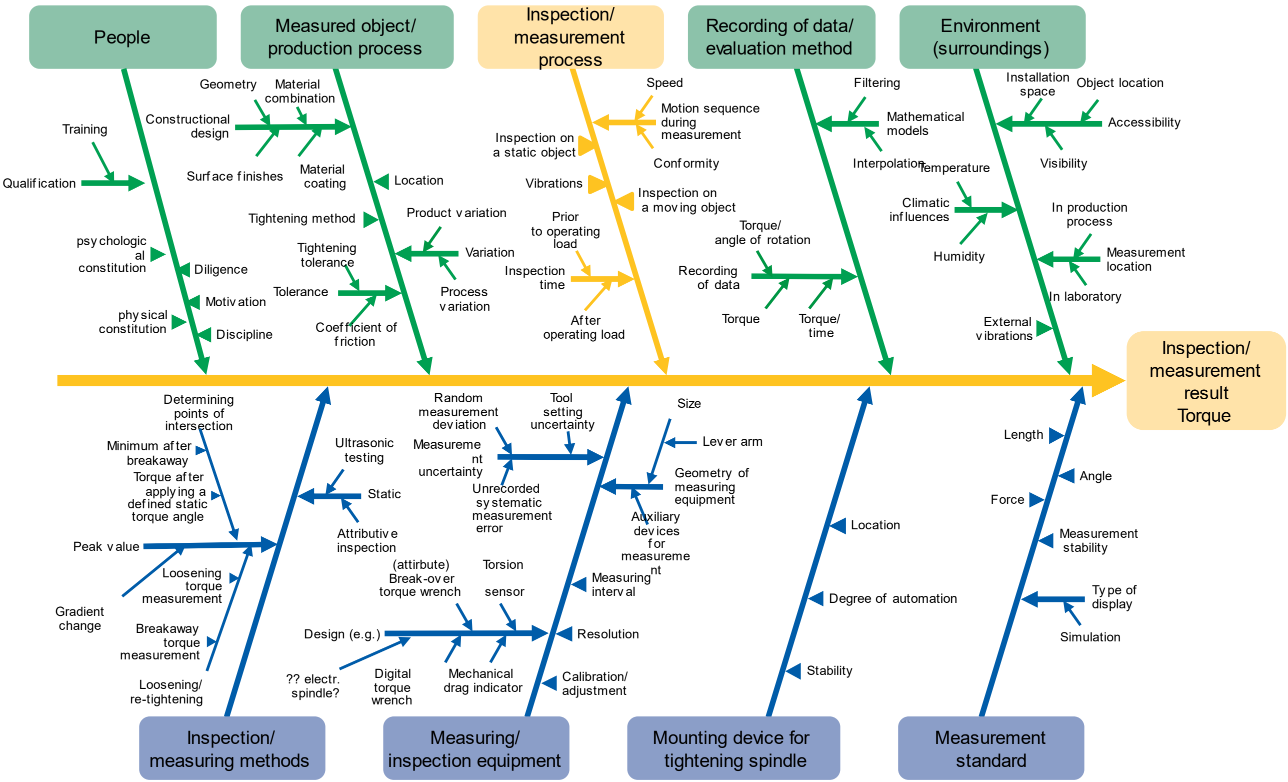
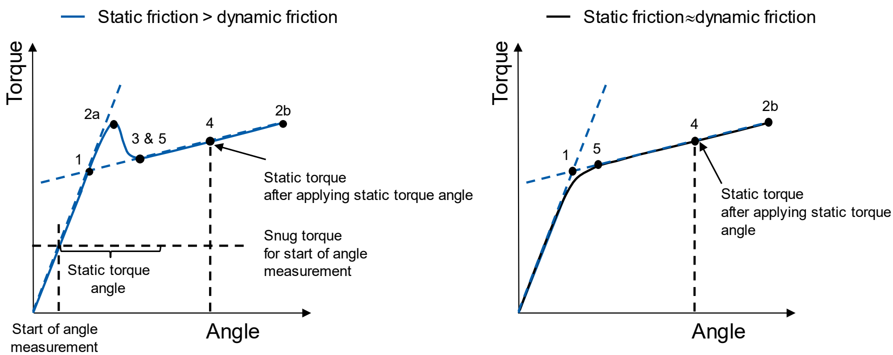


Figure 6-1: Important influences on the uncertainty of measurement results

6.2 Influences of the evaluation method (measuring methods according to VDI/VDE 2645-3 [13])

Depending on manufacturer, measuring device and inspection method, the recorded raw data is processed and evaluated differently. Various interpolations, filterings and smoothings are available for processing data. Depending on the strategy (e.g. determining points of intersection, calculating peak values, minimum after breakaway, torque/angle, gradient change) of the evaluation, different algorithmic models are available in order to determine measurement results (see Figure 6-2). There might therefore be a systematic difference between the determined measurement results. As a consequence, it may be necessary to perform comparison measurements when using different measuring devices.

Note 1: The evaluation software of measuring systems must be validated after any changes to the relevant evaluation software (see VDA 5, Chapter 8.2 “Validation of measurement software”).



1 Determining points of intersection
2a Peak value measurement (at breakaway)
2b Peak value measurement
3 Minimum (after breakaway)
4 Torque after applying a defined static torque angle
5 Gradient change

Figure 6-2: Systematic differences due to different approaches when determining the measurement result

Note 2: If the torque at point 5 is greater than the torque at point 2, this is detected as a maximum in the peak value measurement.

Explanations on the individual points (1-5) are provided in VDI/VDE 2645-3 [13].

6.3 Influences of the measuring / inspection equipment and the auxiliary devices for measurement (measuring device)

Mechanical / geometric influences
The torque-angle curves can also vary due to characteristics like the rigidity/stiffness of the measuring equipment. The measuring system includes the measuring equipment and the auxiliary devices required for measurement. Therefore, it is recommended to standardize the auxiliary devices and to take them into account when it comes to the capability of the measuring device (VDI/VDE 2645-1 [11]). The auxiliary devices include joints, extensions, counterholders, adapters, and guides (supports). Using them can lead to errors due to e.g. play, tilting and loss of efficiency.

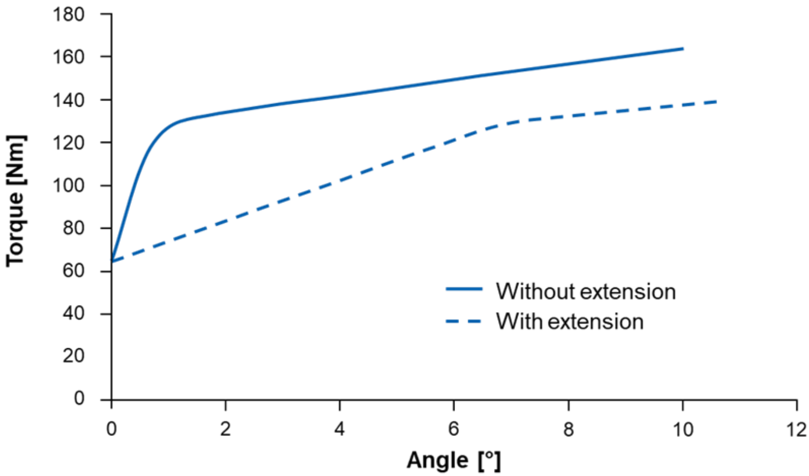


Figure 6-3: Measurement at the same bolt location, with and without extension
Static torque angle of 10° starting from 65 Nm (50% of the nominal torque)

6.4 Influences of the inspection / measurement process

Movement sequence during the measurement
The temporal and spatial motion sequence during a manual measurement (speed, conformity, tilting) may affect the measurement in different ways. As an example, the coefficient of friction can depend on the sliding speed at the contact zones with thread and underhead (see Figure 6-4).

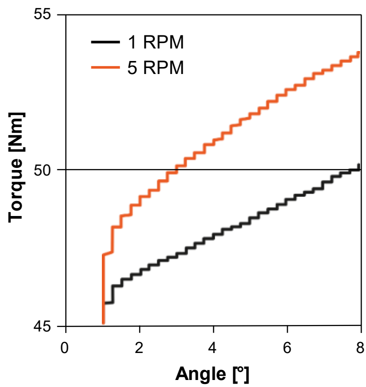


Figure 6-4: Further tightening with 1 RPM and 5 RPM on cathodic dip-paint coating

Inspection on a moving or movable object
Inspections on moving (e.g. component placed on an assembly line) or moveable (e.g. engine in the hanger, rubber-cushioned) objects might falsify the measurement result.
In general, it is preferable to carry out the inspection on a static object. If necessary, the inspected object must be stabilized. In any case, proof of inspection process capability must be obtained for the actual inspection process.

Inspection time
Describes the inspection time after completion of the production process. Different time periods between the installation of the bolted joint and the measurement of the static torque generally lead to different measurement results.
For each bolted joint, the measurement time should always be the same.

The following factors influence the determination of the inspection time: accessibility, application of screws with an adhesive coating, settling and relaxation characteristics, condition of the inspected object (prior to/after operating load), temperature of the part.

In case of fasteners with adhesive coatings, the curing time of the adhesive must be taken into account (the procedures according to DIN 267-27 [6] or the specifications provided by the manufacturer must be followed).

Inspection side in case of through-bolt joints
In case of through-bolt joints (nut + bolt), the measurement is carried out on the same fastener to which the nominal torque was applied. In order to avoid falsified measurement results, it is necessary to counterhold the non-tightened fastener.

6.5 Process sequence for determining inspection process capability

1. Inspection process specification

For each new bolted joint, it must generally be determined whether there is an inspection order. If there is an inspection order, it must be decided which inspection process will be used (see chapter 5). In general, the “static torque" process should be used (see chapter 5.1).
If further tightening is not possible due to framework conditions related to the bolted joint, an alternative inspection must be specified. Examples of alternative inspections are described in chapter 5.2., but are not explored in depth.

2. Specifying the evaluation method

Here, the measurement point for the evaluation is specified, see selection of methods in VDI/VDE 2645-3 [13].

3. Selecting a suitable measuring system

A measuring system is defined as including all measuring equipment as well as auxiliary devices for measurement.
The technical requirements for the measuring equipment are specified:

- Calibration torque and angle
- Capability of measuring device

Further helpful information on the above-mentioned points is provided in VDI/VDE 2645-1 [11]

4. Specifying the two-factor test setup

In order to implement the two-factor test setup, it must first be decided which reference (e.g. measuring brake or component) will be used (see chapter 8).

5. Carrying out the two-factor test

Assessment of inspection process capability according to “method 2” (see chapter 8).

6. Evaluation by means of a mathematical model

The results obtained must be evaluated in the mathematical model Q_{MP} (see chapter 8.2, steps 1-5).

7. Determining inspection process capability

a) The inspection process can be deemed capable if $Q_{MP} \leq \mathbf{30}$ **%.**

b) If this capability cannot be achieved, suitable measures must be taken and the inspection process capability must be re-assessed.

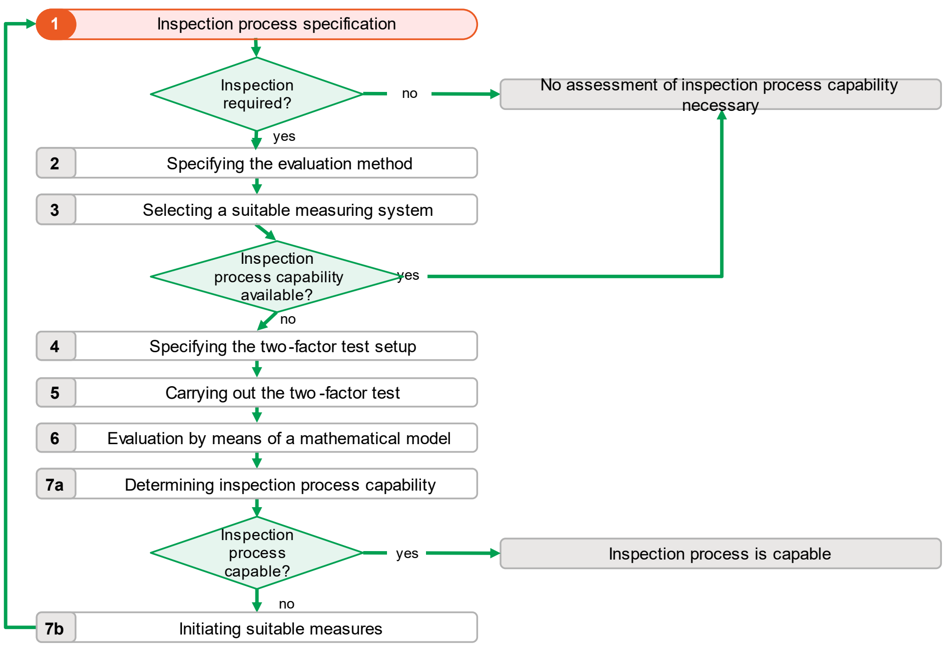


Figure 6-5: Process sequence for assessing inspection process capability

7 Assessment of ongoing capability

For bolted joints, ongoing capability is assessed in the same manner as described in VDA Volume 5, Chapter 10 [1].

In particular, the following aspects must be taken into account:

- auxiliary devices for measurement, e.g. ratchets, extensions, drives
- Changes regarding software and firmware
- Basic settings of the measuring device (e.g. sampling rate, correction factors)

8 Proof of capability

8.1 Preliminary remarks

As noted in the previous chapters, standards cannot be used for bolted joints. Even with simulations on a measuring bench, a test series cannot be conducted with just one sample. Therefore, four individual samples are used in the test described here, given that the measuring bench simulates each test individually. The same applies if inspection process capability is assessed using components

In the study under consideration here, two influencing quantities (factors) were evaluated together. Therefore, the overall variation comprises a mix of these influencing quantities. However, the dispersion of the individual influencing quantities can be calculated separately by using the analysis of variance (ANOVA) method.

A well-known example is the determination of the measurement and inspection process capability, also referred to as “Method 2” . According to this method, both the repeatability and the reproducibility of the operators and the operator/part interaction are determined based on a single study (e.g. two operators, four samples each with three repetitions).

The simulation of a static torque on a measuring brake must be as close as possible to the real bolted joint (hard/soft). I.e. a similar breakaway behaviors in the bolting applications under investigation (significant breakaway vs. no difference between static and dynamic friction) must be simulated.

In case of simulation with a measuring brake, the following aspects must generally be taken into account: Initially, a steep increase in torque must be realised, as when actually tightening a bolt by applying the torque until the bolt head breaks loose, i.e. moves in the same direction in which the torque is applied (see Figure 8-1, area 1). In the area of the desired static torque, a significant drop in torque must then be simulated (seeFigure 8-1, area 2). Depending on the actual bolted joints used in practice, the curve progression before, during and after the simulated breakaway must be simulated. The further progression of the torque simulation is not of particular relevance for all evaluation methods (see Figure 8-1, area 3). In the following example, the gradient change method was used.

The procedure described in this chapter can be applied to all measuring equipment that is described in VDI VDE 2645-1 for carrying out a process capability inspection by means of onward torque measurement, e.g. also for rotating torque/angle transducers or so-called measuring spindles. In the case of automated measurement processes, only the influence of the operator no longer needs to be taken into account.

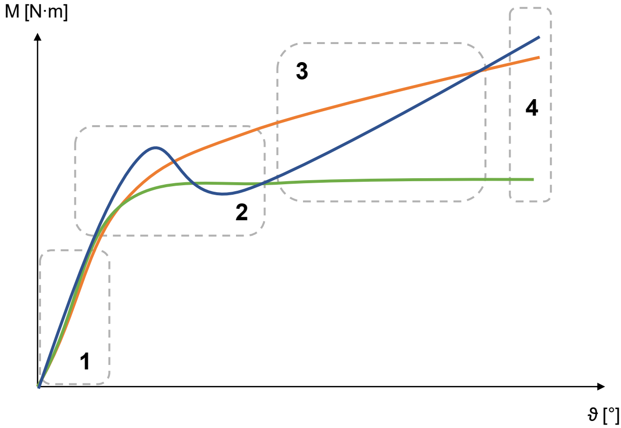


Figure 8-1: Simulation curve measuring brake, areas 1-4

Note 1: The removal behavior in the simulation correspond hapitcally to that of a bolt.

Note 2: For a simulation with measuring brakes, evaluating the torque at the end of the simulation is only useful if this is done within the scope of a measurement in the peak value method (see assessment of the capability of measuring devices according to VDI/VDE 2645-1 [11]). This is because this value represents a “cut-off point” (see Figure 8-1, areas 4), whereas only the dynamic progression of a torque/angle measurement is relevant for static torque measurement.

Note 3: It is not strictly necessary to use a measuring brake. It may for instance also be possible to assess inspection process capability on a real component.

8.2 Proof of capability based on an example (torque wrench)

Step 1: Determining the uncertainty of the measuring system u_{MS} based on the calibration protocol of the torque wrench according to Directive DKD-R 3-7

$$u_{MS} = \frac{Calibration\ step\ (N \cdot m) \cdot Uncertainty\ W\,(\%)}{Coverage\ factor\ k1}$$

$$u_{MS} = \frac{30\ \cdot\ 0.2\ \%}{2} = \frac{30\ \cdot\ 0.002}{2} = 0.03$$

Step 2: Defining the two-factor test plan

Step 2	Factors, number of steps, number of tests, measured values			
Factor A (samples)	Steps n =	4		
Factor B (inspector)	Steps k =	2		
	Tests r =	3		

Figure 8-2: Setup of the two-factor test plan

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

Figure 8-3: Measured values of the samples

Based on the $4 \cdot 2 \cdot 3 = 24$ measured values and the desired coverage of 95.45%, the coverage factor must be adjusted:

$\boldsymbol{k2 = 2.1147}$.

Step 3: Determining the uncertainty of the measurement process u_{MP} by means of commercial software (exclusion of interactions/correlations: 5 %)

R&R (total)

Source	Standard deviation	Variation (6 × SA)	% Variation (% SU)	% Tolerance (SU/Tol)
R&R (total)	0.463498	2.78099	100.00	34.76
Repeatability	0.211808	1.27085	45.70	15.89
Reproducibility	0.412271	2.47363	88.95	30.92
Inspector	0.412271	2.47363	88.95	30.92
Between parts	0.000000	0.00000	0.00	0.00
Total variation	0.463498	2.78099	100.00	34.76

Figure 8-4: Extract of the calculations of a random measurement software (example)

Step 4: Determining the combined uncertainty u_{MP}

$$u_{MP.combined} = \sqrt{(u_{MS})^2 + (U_{MP})^2}$$

Step 5: Determining the capability Q_{MP} with a tolerance

$$T = (20\ N \cdot m\ \cdot 1.2) - (20\ N \cdot m\ \cdot 0.8) = 24 - 16 = 8$$

$$Q_{MP} = \frac{2 \cdot k2 \cdot u_{MP.combined}}{T} = \mathbf{24.84\%}$$

Since $Q_{MP} \leq \mathbf{30}\ \%$, the measurement process is deemed **capable**.

8.3 Version “Step 3 without commercial software (illustrated principle)“

3a **Faktoren, Anzahl Stufen, Anzahl Versuche, Messwerte erfassen**

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

3b **Für jede Stufe (Quadrierte Summe der Messwerte)/(Anzahl Stufen * Anzahl Versuche)) berechnen**

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4	
B.1	19,856	20,087	20,064	20,265	
	20,346	20,048	20,427	20,117	
	20,463	20,027	19,651	19,759	4844,5027
B.2	20,798	20,83	20,719	20,655	
	20,604	20,441	20,715	20,532	
	20,593	20,859	20,687	20,75	5132,9001
	2507,5793	2492,55554	2491,3735	2483,8397	

3c **(Quadrierte Summe aller Messwerte)/(n*k*r) berechnen**

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4	
B.1	19,856	20,087	20,064	20,265	
	20,346	20,048	20,427	20,117	
	20,463	20,027	19,651	19,759	4844,5027
B.2	20,798	20,83	20,719	20,655	
	20,604	20,441	20,715	20,532	
	20,593	20,859	20,687	20,75	5132,9001
	2507,5793	2492,55554	2491,3735	2483,8397	

0,0297 Summe 3b-3c

9975,3183

3d **Für jeden Faktor ((Summe Ergebnisse aus 3b)-(Ergebnis aus 3c) berechnen**

394,260736
413,959716
418,734369
432,556804
424,524816
424,071649

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4	
B.1	19,856	20,087	20,064	20,265	
	20,346	20,048	20,427	20,117	
	20,463	20,027	19,651	19,759	4844,5027
B.2	20,798	20,83	20,719	20,655	
	20,604	20,441	20,715	20,532	
	20,593	20,859	20,687	20,75	5132,9001
	2507,5793	2492,55554	2491,3735	2483,8397	
	1226,7474	1206,48875	1205,6867	1205,6466	
	1281,1267	1286,7123	1286,3395	1278,730656	

2,1142

0,0297 Summe 3b-3c

3e **Für jede Stufe der Faktoren A und B ((Quadrierte Summe der Messwerte)/Versuche) berechnen**

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

394,260736
413,959716
418,734369
432,556804
424,524816
424,071649

4844,5027

5132,9001

2,1142

2507,5793 2492,55554 2491,3735 2483,8397

0,0297 Summe 3b-3c

1226,7474 1206,48875 1205,6867 1205,6466
1281,1267 1286,7123 1286,3395 1278,730656

3f **(Summe Ergebnis aus 3e)-(Summe Ergebnis aus 3b)+(Ergebnis aus 3c) berechnen**

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

394,260736
413,959716
418,734369
432,556804
424,524816
424,071649

4844,5027

5132,9001

2,1142

2507,5793 2492,55554 2491,3735 2483,8397

0,0297 Summe 3b-3c

1226,7474 1206,48875 1205,6867 1205,6466
1281,1267 1286,7123 1286,3395 1278,730656

0,0462
2,9666

3g **(Summe aller quadrierten Messwerte)-(Ergebnis aus 3c) berechnen**

394,260736
413,959716
418,734369
432,556804
424,524816
424,071649

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

4844,5027

5132,9001

2,1142

2507,5793 2492,55554 2491,3735 2483,8397

0,0297 Summe 3b-3c

1226,7474 1206,48875 1205,6867 1205,6466
1281,1267 1286,7123 1286,3395 1278,730656

0,0462
2,9666
0,8062

3h **(Ergebnis aus 3g)-(Ergebnis aus 3d)-(Ergebnis aus 3f) berechnen**

394,260736
413,959716
418,734369
432,556804
424,524816
424,071649

Faktor **A**	Stufen n =	4
Faktor **B**	Stufen k =	2
	Versuche r =	3

	A1	A2	A3	A4
B.1	19,856	20,087	20,064	20,265
	20,346	20,048	20,427	20,117
	20,463	20,027	19,651	19,759
B.2	20,798	20,83	20,719	20,655
	20,604	20,441	20,715	20,532
	20,593	20,859	20,687	20,75

4844,5027

5132,9001

2,1142

2507,5793 2492,55554 2491,3735 2483,8397

0,0297 Summe 3b-3c

1226,7474 1206,48875 1205,6867 1205,6466
1281,1267 1286,7123 1286,3395 1278,730656

0,0462
2,9666
0,8062

3 i	Aus den Ergebnissen von 3d,3f,3g,3h Anova Tafel aufstellen				
Anova	SS	DF	MS=SS/DF	Prüfwert	
PV	0,0297	3	0,010	MS_{PV}/MS_{EV}	0,20
AV	2,0845	1	2,084	MS_{AV}/MS_{EV}	41,37
IA	0,0462	3	0,015	MS_{IA}/MS_{EV}	0,31
EV	0,8062	16	0,050		
Total	2,9666	23			

3 j	Pooling, Streuung, Unsicherheit berechnet				
Anova	SS	DF	MS=SS/DF	Erwartete Streuung	
AV	2,0845	1	2,084	2,4736	$6*\sqrt{(MS_{AV}-(MS_{IA}+MS_{EV}))/n*r}$
IA+EV	0,8524	19	0,045	1,2708	$6*\sqrt{(MS_{IA}+MS_{AV})}$

U_{MP}	
0,4635	$(\sqrt{((\text{Erwartete Streuung}_{AV})^2+(\text{Erwartete Streuung}_{(IA+EV)}))/6)}$

8.4 Typical measurement process models

It is useful to display the measurement processes in a measurement process model matrix. The specifications of a basic measurement model are described in the following and can be used in order to release wrenches/types/
manufacturers on the basis of standardised assessments of inspection process capability (see examples of measurement process models,table 6-3, VDA Volume 5, Chapter 6 [1]):

- Manufacturer specifications (e.g. area of application, temperature, humidity)
- Upper and lower measurement range
- Tolerance
- Evaluation method
- Removal speed
- Curve characteristics
- Proof of capability of the software (see chapter 8.2 in VDA Volume 5 [1])

- Simulation parameters (e.g. angular degrees set on the measuring brake)
- Further relevant characteristics

It is also possible to have service providers carry out the assessment of inspection process capability with the indicated aspects, either in whole or in part.

Note: Type approval based on the capability of measuring devices according to VDI/VDE 2645-1 [11] (determination of Cg / Cgk) is not permissible. In addition to calibration, the capability of each piece of measuring equipment must be assessed (see chapter 2). However, in contrast to the calibration, capability must only be determined once prior to first use or after repairs/intervention in the measurement chain.

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10 Index of Formula Symbols

Symbol	Designation
α	Pitch angle
α_A	Tightening factor
μ_G	Coefficient of friction in the thread
μ_K	Coefficient of friction in the head bearing area
d_2	Pitch diameter
D_{Km}	Effective diameter for the friction torque in the bolt head or nut bearing area
F	Force
F_M	Assembly preload
F_{Mmin}, F_{Mmax}	Minimum, maximum assembly preload
FV	Preload (after settling)
k	Coverage factor
M_{nom}	Nominal torque
M_G	Thread friction torque
M_K	Head friction torque
M_{LG}	Torque to untighten/loosen definition according to VDA 235-203 [5]
M_{LH}	Breakaway torque in loosening direction definition according to VDA 235-203 [5]
M_{St}	Pitch torque
M_{WG}	Static torque definition according to VDA 235-203 [5]
M_{WH}	Breakaway torque during further tightening definition according to VDA 235-203 [5]
N	Number of measured values
P	Thread pitch
Q_{MP}	Capability ratio (measurement process)
Q_{MS}	Capability ratio (measuring system)
$Q_{MS.max}$	Capability ratio limit (measuring system)
u_{MP}	Uncertainty of the measurement process
u_{MS}	Uncertainty of the measuring system
U_{MP}	Combined standard uncertainty (measurement process)
U_{MS}	Combined standard uncertainty (measuring system)