Uncertainty of Measurement in Torque Wrench Calibration

Speaker/Author: Luca G. Bochese,
Co-author: Carlo Ferrero, IMGC, Torino, Italy
Boch / Feanor Metrology
Via Montepulciano 8
I-20124 Milano (Italy)
Email: info@boch.net
Phone: (+39) 348 412-1280, FAX: (+39) 02 70053-2664
www.boch.net, www.feanor.com

Torque wrenches (TW) are often considered and used as “tools” (such as screwdrivers and similar), rather than true measuring “instruments”. They provide a “visible” measure of torque (dial indicating, flat beam TW) or are used to control torque in assembly and fastening operations (slipper, clicker-TW). Calibration procedures for hand torque tools are defined by the ISO 6789:1992 standard, which does not provide any information or guideline on how to evaluate the uncertainty of measurement. This report analyses the situation in EU calibration laboratories, key issues and methods in calibration of hand torque tools in the calibration lab and the industry. It also suggests a basic measurement uncertainty budget. These information can be relevant for quality managers with the need to set up a torque wrench calibration facility in their own company.

1. Hand torque measuring “tools” or “instruments”?

Control of the applied torque is required especially when particular materials or gaskets are being used with bolts/nuts connections. Industries facing possible safety (pressure containers, nuclear, aerospace, etc.) or guarantee issues (i.e. automotive) do actually perform, also for this type of tools, calibration, time stability and R&R (repeatability and reproducibility) studies. Nevertheless, this activity has normally a lower priority, compared to i.e. management and calibration of dimensional measuring instruments.
Measurement of torque in production is generally performed with hand torque measuring tools, more generally defined as "assembly tools for screws and nuts". They can be divided in two classes: "dial indicating” or "clicker" tools, defined in ISO 6789:1992 (see figure 1). We describe here only the most important ones:

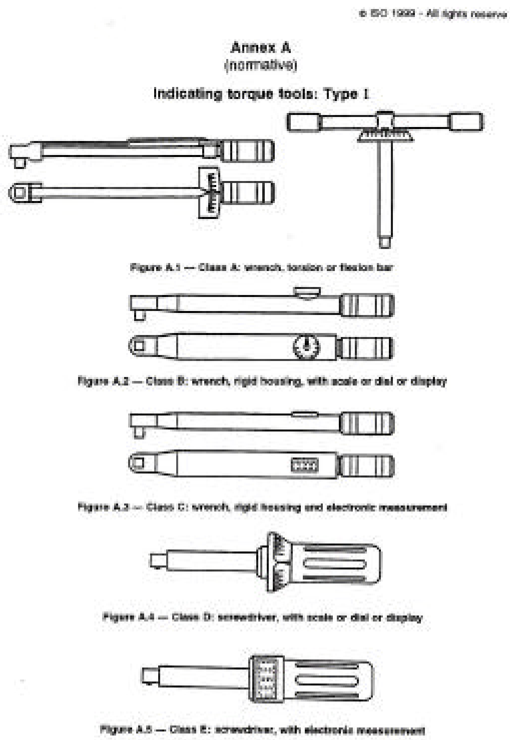

Figure 1. Classification of indicating torque tools.

1.1 Dial indicating torque wrenches

These TW are designed for the precise application and measurement of any torque value, without the need for ancillary calibration or setting equipment. They usually have bi-directional tightening. The instant torque value is displayed continuously on an analogic or digital display (see figure 2), the user looks at the display while operating the tool and stops tightening when the desired torque value is achieved. Being used as an “instrument”, these TW usually provide good results, and have generally a good repeatability and a medium reproducibility.


Figure 2. Dial indicating torque wrench 8-40 Nm (72-360 lbf.in).

1.2 Click torque wrenches (adjustable by the user)
In this case, the required nominal value is pre-set on an indicator (a scale) by the user, the tool is then used as a normal spanner, often without a particular "care" in operation. When the required torque is reached , the tool switches with a perceptible, unmistakable and audible click (see figure 10). At that point the user should immediately stop tightening.
These TW are used in many different tightening applications, in assembling departments, in workshops, and they are easy to be found in all car repair workshops, where a "flexible" tool is required for various tasks. This flexibility leads to a lower repeatability and reproducibility of the required torque value.


Figure 3. Clicker torque wrench from 1 to 12 Nm.(10-100 lbf.in.)

Figure 4 shows the inside structure of a clicker-TW, with a multi-lever action. The spring in the hilt applies a force against one or more elements, which are connected, through a multi-lever system, to the square drive. Setting the TW means compressing the spring and applying a higher force to the elements. When the user operates the TW and the force balance is reached, there is a

click point (peak value) and an immediate decrease of the torque value (see figures from 10 to 12 for the typical behavior of clicker-TW).
The capacity of converting exactly the force F applied from the spring (N) in the required torque (Nm) and the “repeatability” of this “transformation” are the secrets of a "good" clicker-TW design.

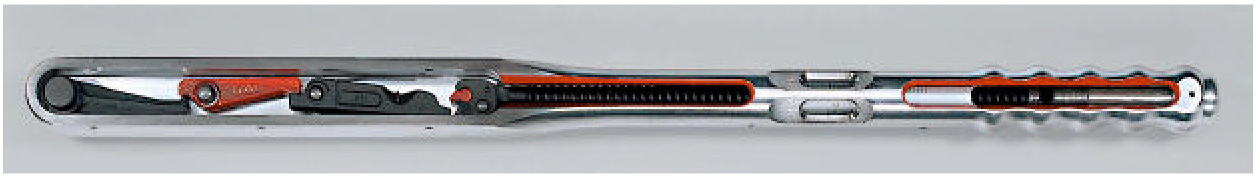

Figure 4. Multi-lever inside mechanism of a clicker torque wrench.

1.3 Slipper torque wrenches
A variant of the previous one, this TW type cannot be adjusted directly by the user, as it doesn’t have a setting scale or indicator. It is also known as “production type TW”, is normally set against a torque wrench analyzer or calibration device TWCD (see figure 6) and then dedicated to a particular application, where modifications of the value of the nominal torque are not frequently required. From the metrological point of view, this is the “safest” tightening system, as it eliminates over-tightening and discourages unauthorized alteration. It has a smooth decreasing curve after the peak value, with the typical behavior shown in figure 15.

Figure 5. Slipper torque wrench (production type)

2. The situation in Europe
The lack of ”metrological awareness” for these kind of instruments leads, in general, to a poor overall quality level of “controlled fastening”.
Traceability of measured quantities to corresponding national references (metrological chain) is not so well established for “torque”, compared to other quantities (for which, in effect, “tangible” reference standards do exist).
Torque calibration is usually related to departments, in National Metrological Institutes (NMI), dealing with Force and Mass, but in many European countries NMIs do not perform calibration

of torque wrenches. Calibration is limited to torque transducers [3], using beam and weighs systems (in connection with the Mass department).
Calibration of TW is therefore normally performed by accredited calibration laboratories (ACL).

3. MUTORQUE proposal

In order to harmonize calibration procedures and improve the mutual recognition of calibration certificates, there is a strong need for a standard guideline for determining the uncertainty of measurement.
For this reason, an Integrated Project proposal has been recently presented (Acronym MUTORQUE) for evaluation by the 6th Framework Program of the European Union [4].
Research Institutes and ACLs from Estonia, Czech Republic, France, Italy, Sweden, Switzerland, as well as TW manufacturers from Germany and the UK are involved in this project, with the aim to provide a common guideline for TW calibration and uncertainty evaluation, possibly at EA [2,3] or ISO [1] level, to improve the design of existing TW types and their performance, and to make results available on a specific webpage.

4. Calibration of torque wrenches

Calibration according to ISO 6789:1992 requires five consecutive clicks, without recording the measure, at the maximum nominal torque (MNT), followed by the measurement of five consecutive positions at 20%, 60% and 100% of the MNT.
If none of the 15 measured values is outside the tolerance values (defined as 4% of the nominal value) the TW is considered conforming according to ISO 6789:1992.
In the example in figure 9 the click points of the TW, preset at 20, 60 and 100 Nm, would have to be respectively within following ranges (19,2 –20,8 Nm) (57,6 - 62,4 Nm), (96 -104 Nm).
Calibration can be performed with automatic or manuals devices. Automatic devices are normally used by calibration laboratories, while manual devices, with a higher uncertainty of measurement, are used in company calibration labs.

4.1 Manual calibration devices (testers) for torque wrenches

Devices like the one shown in figure 6 can be used by companies as “master calibration device” by companies, to perform internal calibration or setting of torque wrenches.
They are also used by some calibration laboratories, but they show a relatively higher uncertainty, compared to automatic systems.
To improve the reproducibility of the click points (influence of different users), the TWCD is located on a light and rigid aluminum structure. The crank on the sliding carriage allows a more continuous and linear application of the force.

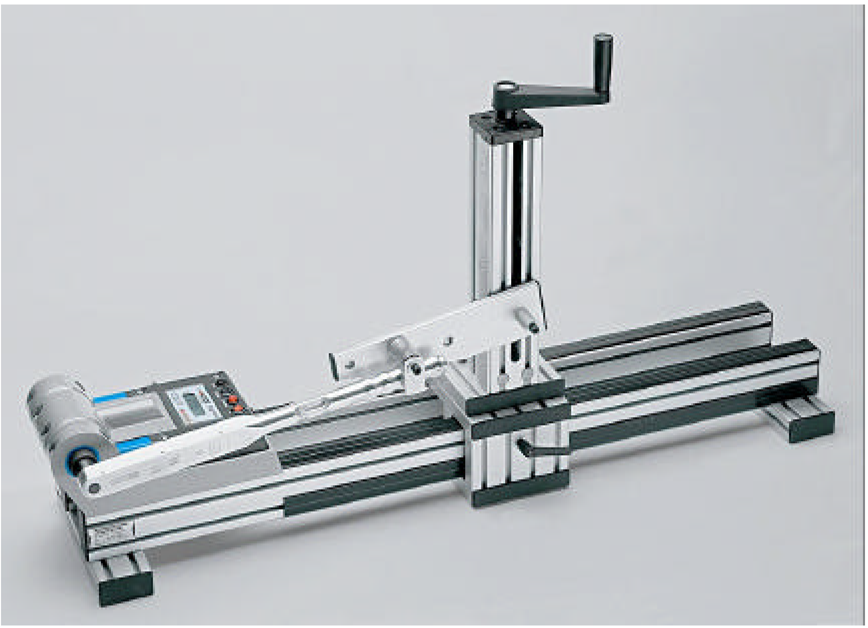
Figure 6. Manual calibration device for torque wrenches. [8]

4.2. Automatic calibration devices for torque wrenches

An automatic calibration device, for laboratory use, is shown in figure 7. The torque is applied by a motor, connected to the reference torque transducer and, through a two-speed gear box, to the TW in calibration.

When torque is applied by the motor, the transducer acquires up to 2000 measuring values every second and draws torque vs. time graphs. The software identifies the maximum value, compares it with the nominal value and print a calibration report according to ISO 6789:1992 and/or torque vs. time characteristic curves (figures 10 - 15).

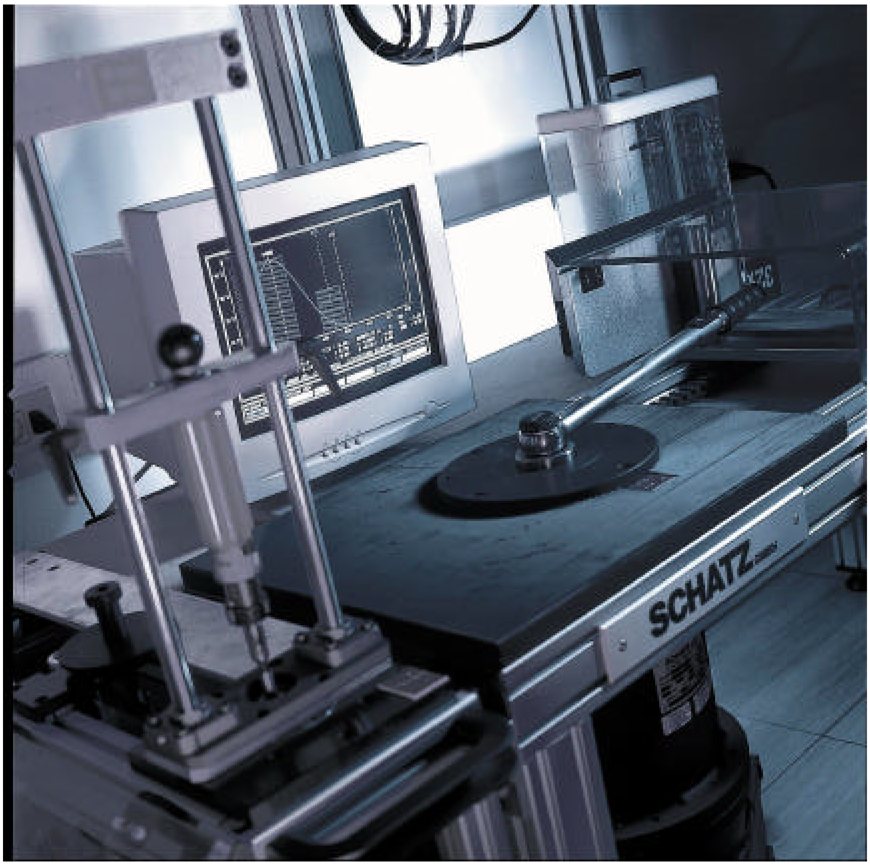

Figure 7. Automatic calibration device for torque wrenches. [9]

5. Software for calibration of torque wrenches

Figure 6 shows an example of a software being used for calibration of TW [6], allowing the acquisition of the measured values, management of different instruments (calibration due-date, history, etc.) and print of calibration / test certificates according to ISO 6789:1992.
Initially developed for length metrology, it is now being completed with a standard module for the evaluation of uncertainty of measurement (MUTORQUE).

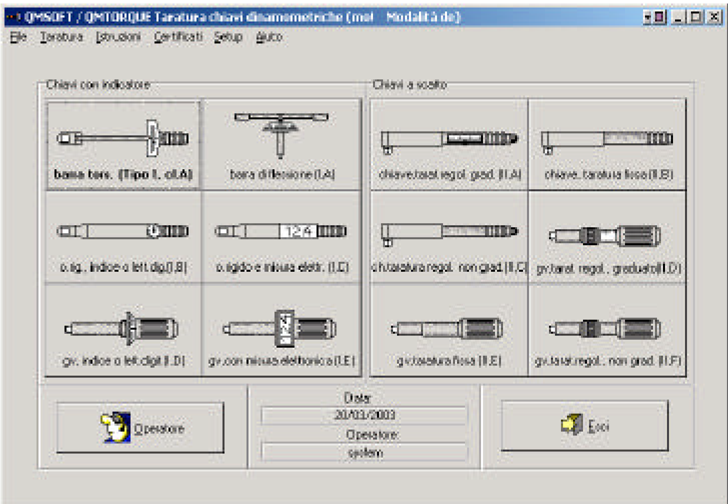

Figure 8. Types of torque wrench defined by ISO 6789:1992. [7]

5. Key issues on calibration and use of torque wrenches

5.1 Initial shock

The following graph shows a typical measuring sequence on a common clicker-TW, set at 20 Nm (14.74 lbf.ft).

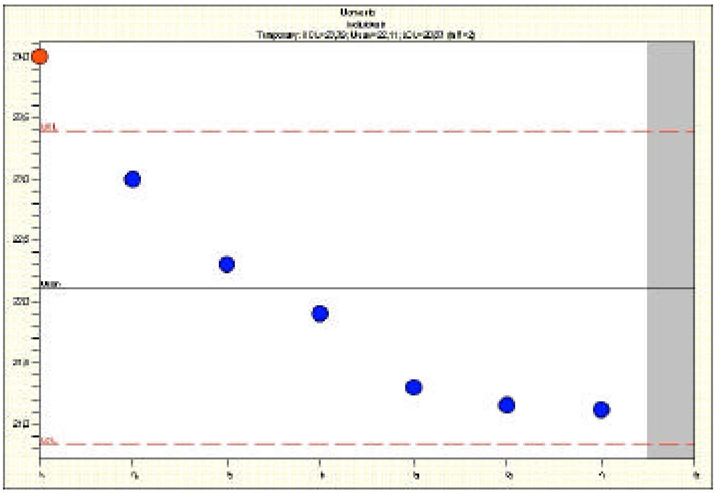

Figure 9. Typical sequence of consecutive click points

The first click (usually only this one, sometimes the first two points) falls very often outside the upper 4% limit. Measurement values decrease gradually and stabilize after a few clicks.
This is the main reason why ISO 6789:1992 requires five initial clicks at the MNT **before** taking any measurement. Experience shows that the effects of this “initial shock” do not prevent the TW from having the same behavior **during** calibration, when measurements are taken. The initial click, therefore, often falls outside the upper 4% tolerance value even for relatively “good” torque wrenches.
This behavior also points out a strong correlation of the measured values and makes the evaluation of the uncertainty of measurement more difficult. We cannot assume a Gaussian distribution for this process. We should also consider that this phenomenon is not identical for all the types of torque wrench designs, and depends from many sources, which are being studied by the MUTORQUE team. For these reasons we suggest a conservative top-down approach (see chapters 6 and 7).

5.2 Torque vs. time behavior

By analyzing different TW types and looking closely what happens in proximity of the click point, we can pinpoint some issues in TW calibration.
Figures 10, 11 and 12 represent the ideal situation, a well defined peak value, an almost immediate and consistent decrease, which can be clearly identified by the user.
It is not possible to avoid completely the increase in torque after the click, with click torque wrenches.

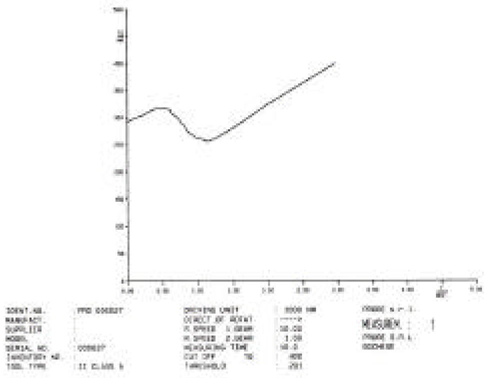

Figure 10. A good torque wrench shows a well remarkable peak, corresponding to the pre-set torque value.

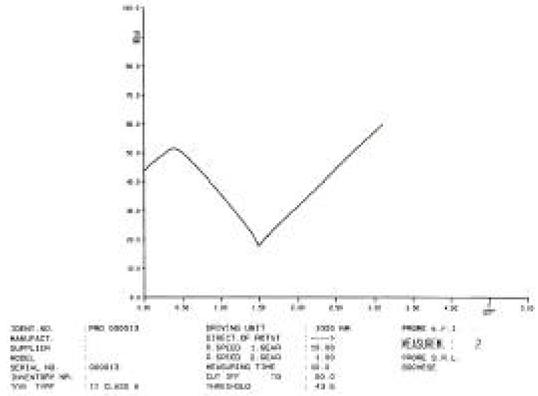

Figure 11. In this case the click is even more clear and easier to be identified.

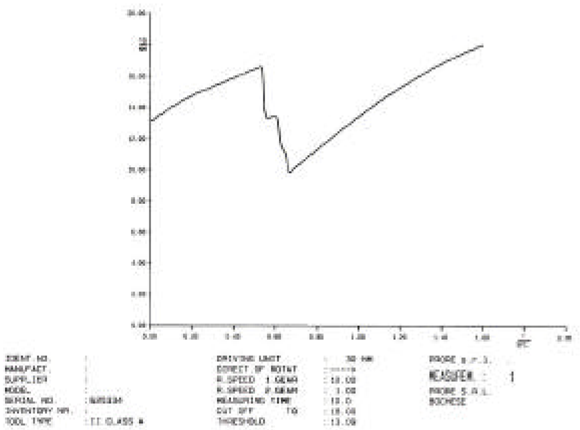

Figure 12. A variation like this can also be admitted, provided that the click point can be easily identified.

Let’s have a look at some “undesirable” behaviors. The irregular curve shown in figure 13, with many local peaks, relatively close to each other, can confuse the user and reduce tightening accuracy.

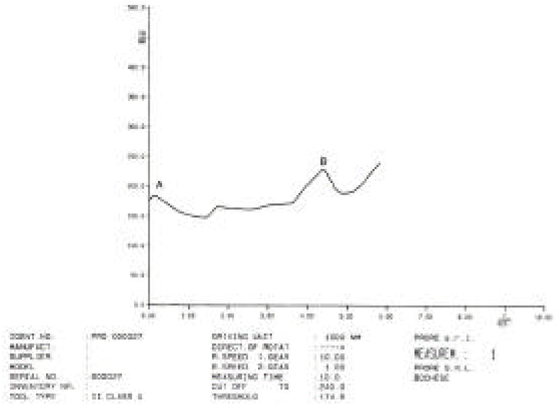

Figure 13. In this undesirable situation, the user is not able to identify correctly the click point.

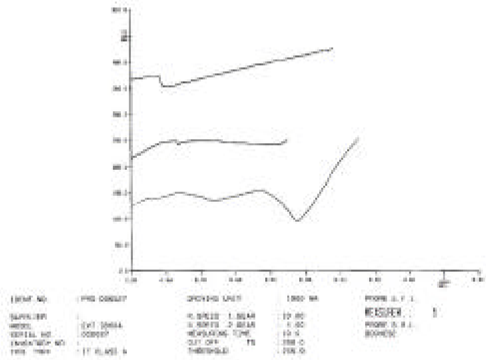

Figure 14. Other irregular patterns. Only a well trained user can identify the click point on the upper graph.

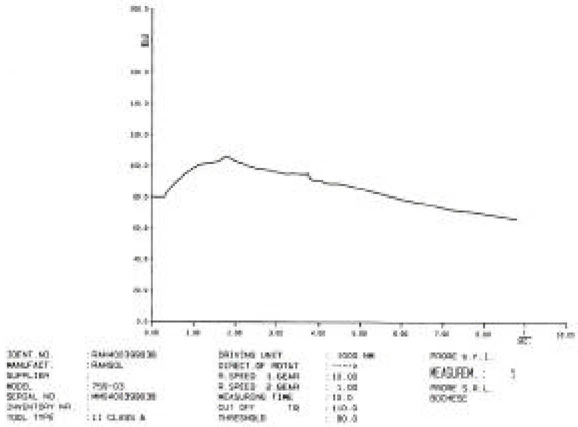

Figure 15. Typical behavior of a slipper TW. The advantages of using a slipper TW are even greater if the torque decreases, as shown here, after having achieved the peak value.

5. 3 Short-term time effect

Figure 16 shows a sample of twenty consecutive measurements on the same TW, set at 20 Nm (14.74 lbf.ft) and operated at time intervals of 2, 120 and 300 seconds on an automatic calibration device. The first click point has always been considered in the calculations. The TW has been turned down (spring unloaded) for at least 6 hours, between a sequence of 20 measures and the following sequence, in order to reduce interactions between sequences. The graphs are similar and show a correlation between torque and tightening frequency. Users should be made aware of this behavior.

An interval of 2 seconds (blue) between consecutive releases is not enough for the spring to go back to its original length, the click is always at a lower torque (even after the first 10 clicks).

The green (t=120s) and brown (t=300s) curves are very similar.
Experience also shows that a longer the interval between clicks leads to overall click point values, the difference here is around 0.7 Nm (0.51 lbf.ft). The graph shows that the spread of measurement values reduces after about 10 clicks or more.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2 sec	19,65	19,54	19,30	19,18	19,08	18,90	18,98	18,90	18,90	18,79	18,78	18,71	18,71	18,69	18,64	18,69	18,63	18,65	18,64	18,60
20 sec	19,30	19,17	19,04	18,98	18,92	18,92	18,93	18,90	18,95	18,94	18,85	18,84	18,83	18,82	18,87	18,75	18,77	18,74	18,78	18,78
00 sec	19,95	19,42	19,25	19,18	19,13	19,11	19,07	19,04	19,02	19,07	19,02	18,99	18,99	18,97	18,97	18,97	18,95	18,94	18,89	18,89

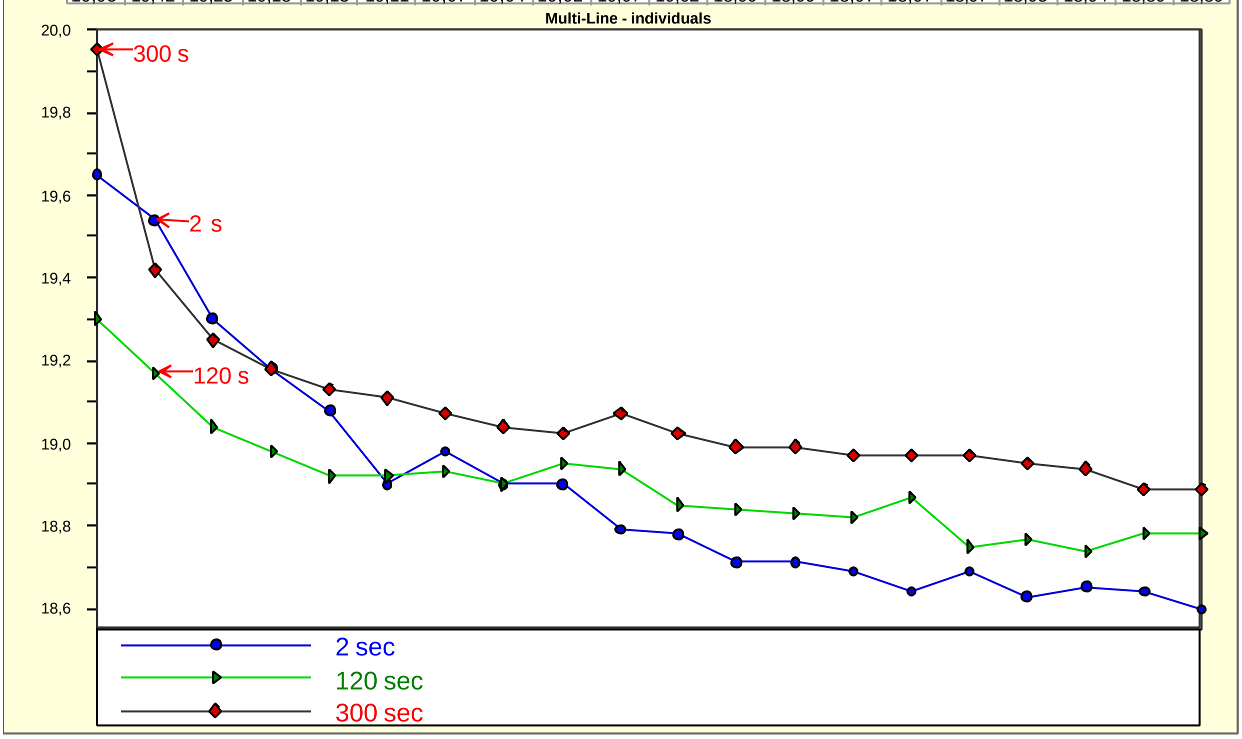

Figure 16. This figure shows sequences of release points after different time intervals (2, 120 and 300 seconds). [6]

This is an example of the analysis being performed by MUTORQUE, with the aid of ANOVA, (DOE) design of experiments, R&R and other statistical tools [6].
Regression equations for different type of torque wrenches are also being determined on large samples of similar torque wrenches, and being saved in a laboratory databank (MUTORQUE).

5. 4 Long-term time effect

From the above pattern we saw a short-term interaction between the click point number and the time. Unfortunately, there is also a long term effect, which is often not considered by TW users. Clicker-type TW should always be turned down and stored at the lowest possible setting, but this is usually not the case. The continuous “stress” on the internal spring can be responsible for a long-term decrease in performance (accuracy). It is necessary, before performing calibration, to keep the torque at the minimum setting for a certain amount of time (12 hours), in order to exclude or reduce this effect.

5.5 The importance of the firs click points

The importance of the first click points is clear when examining the histograms simulating "populations" of consecutive clicks measured in a determined position. This histogram shows 60 measures, taken in 3 consecutive cycles, each one with 20 consecutive click points, including also the first click. The distribution is clearly skewed.

How many click points should we remove, in order to have a normal (Gaussian) distribution?. We use the Chi-square test to define when the distribution can be considered as a normal one.

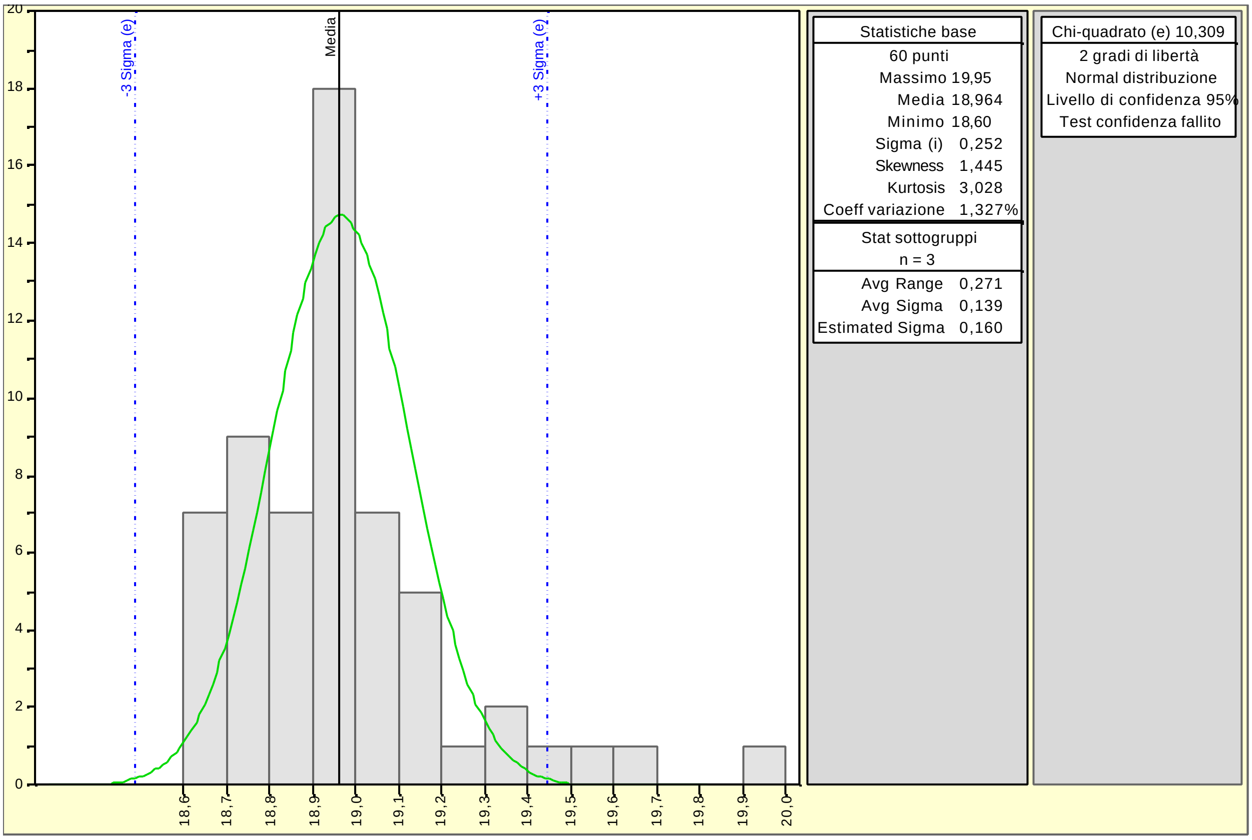

Figure 17. Sample of 60 measures, including the first release points. [6]

By excluding the first click point, and repeating each time the chi-square test, we find out that the distribution is gaussian when we remove the first four points for each sequence.

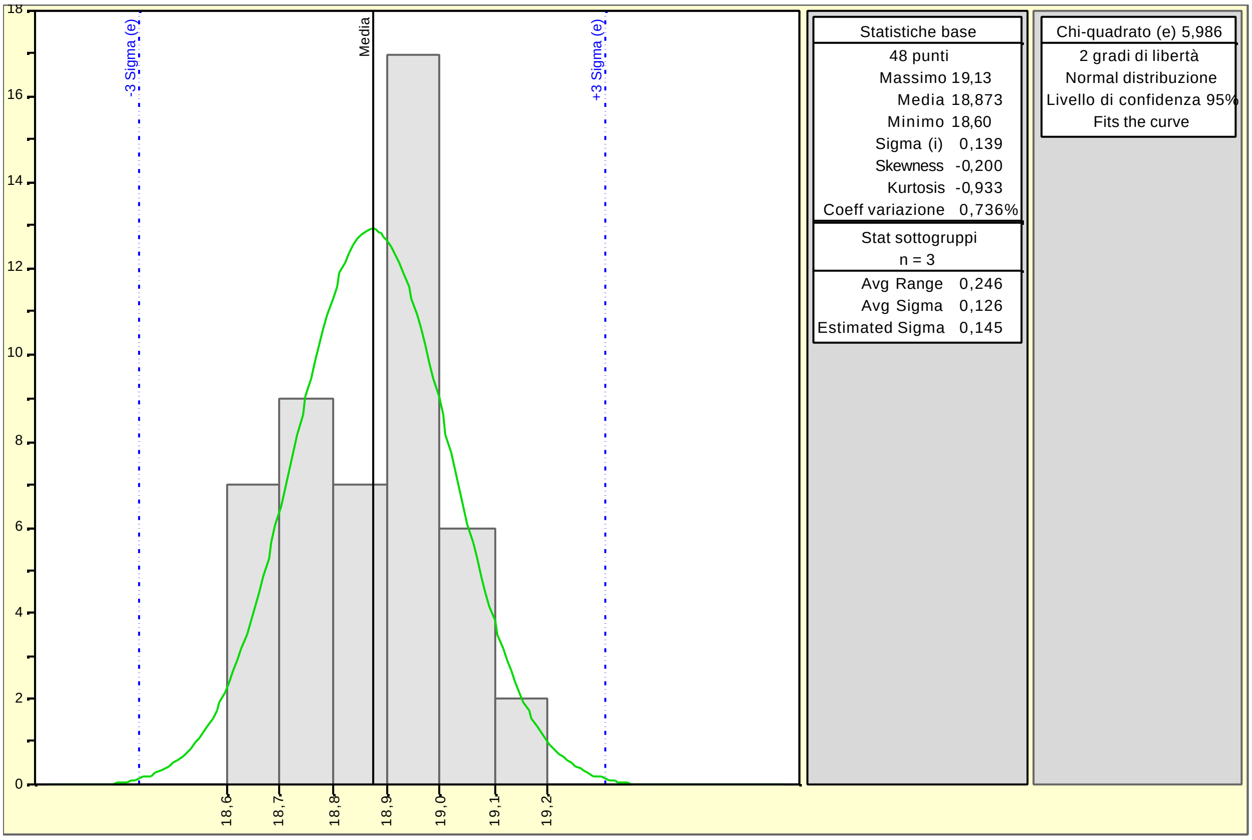

Figure 18. Histogram obtained by removing the first four click points for each sequence. [6]

6. Evaluation of the uncertainty of measurement

The following example (top-down approach with an over-estimation) refers to a calibration of a TW with an TWCD (figures 6 and 7) and should be taken as a preliminary example, not as an official and general way of determining uncertainty in torque calibration.
It might be used, in principle, at the factory level, since it considers globally only three elements (reference standard, TW design and user) in determining the expanded uncertainty of measurement.
Please refer to the official MUTORQUE webpage for a bottom-up approach, with an analysis of characteristics of torque vs. time graphs for existing TW models and different evaluation models. Such an approach will be soon available, as well as improvement of the method proposed here. Calibration with devices different from those of figure 6 might also include other contributions, such as the resolution of reference transducer display (if calibrated separately from the transducer), drift of standard, reproducibility, etc.

Following contributions can generally be taken into account:

- Contribution of the second line reference ($\mathbf{u}_{CSL}$), which is basically the torque transducer of the TWCD. This value should be taken from the manufacturer's calibration certificate, for the corresponding measuring range or defined position, divided by the coverage factor (usually k=2). It’s not unusual to take the maximum value of the expanded uncertainty (i.e. 1%), convert it to Nm and then consider 0.5%. If the ATWCD shows a drift over time, another source of uncertainty should be added, based on historical data of calibration certificates or experience. In the numerical example we prefer to take the actual value 0.270 Nm, corresponding to the 0,27% in the 100 Nm position (interpolation can be necessary if that particular calibration position is not included in the certificate), and obtain 0.135 Nm.

- Contribution of the resolution (**u_r**). With this contribution we simply refer to the user’s error when setting the required torque value on the TW scale. This can roughly be related to the scale resolution r, divided by a standard value. TW with a lower resolution (i.e. 1 Nm) can slightly reduce this contribution. We optimistically suggest to have a “normal distributed” user, divide the resolution by a factor 5 (20%) and then take ½ of this value. Some calibration laboratories consider a rectangular distribution and divide this value by $\sqrt{3}$. In this particular case our value would then be 0.577 Nm instead of 0.500 Nm.

- Contribution of the TW inherent repeatability (**u_b**). We can try to define here the key issues discussed in the previous paragraphs and evaluate it, to be on the safe side, with the sample standard deviation (s) of the 5 measurements in each position according to ISO 6789:1992. To be on the safe side, we include the first click point. We consider this contribution as a type A uncertainty and we do not divide this value by the coverage factor.
  Note: use (n-1) at the denominator when evaluating s.

- Contribution of reproducibility, imperfect connection of TW and TWCD fittings, local deformation, friction and other factors. Their contribution, especially reproducibility, has already been considered in u_r, with the r/5 value (presumably high enough).

- Contribution of environmental factors such as temperature, humidity, pressure, etc. They are not considered as relevant, we consider T = 22.0 ± 3 °C (71.6 ± 5.4 °F), humidity lower than 70% and a temperature variation less than 1 °C (1.8 °F) during calibration (which takes about 20 minutes).

To simplify, we assume no correlation and then have, according to [2]:

$$U = k \cdot u(\overline{X})$$

with

$$u(\overline{X}) = \sqrt{(u_{CSL}^2 + u_b^2 + u_r^2)}$$

Symbol	Source of uncertainty	Value Nm	Distribution	Divisor	u Nm
u_{CSL}	Uncertainty of TWCD	CD manufacturer's calibration certificate	normal	2	½ of the value of the expanded uncertainty on the calibration certificate, if given as k=2
u_b	Contribution of the inherent TW repeatability	sample standard deviation	normal	1	sample standard deviation
u_r	Contribution of the user	r/5	normal	2	r/10
u	Combined uncertainty		normal		u
U	Expanded uncertainty		normal, k=2		U

Table 1. Example of a budget for the uncertainty of measurement

7. Example

Calibration position: 100 Nm
Nominal value of ATWCD: 100 Nm
TW resolution: 5 Nm
TW measurement values:

101.00	100.00	99.00	98.50	98.00

mean value of the 5 measurements = 99.300 Nm
standard deviation = 1.204 Nm

Symbol	Source of uncertainty	Value Nm	Distribution	Divisor	u Nm
u_{CSL}	Uncertainty of TWCD	0.270	normal	2	0.135
$u_{b'}$	Contribution of the inherent TW repeatability	1.204	normal	1	1.204
u_r	Contribution of the user	1	normal	2	0,500
u	Combined uncertainty				1,310
U	Expanded uncertainty				**2.621**

Table 2. Numerical budget for the uncertainty of measurement

The uncertainty of measurement of the torque wrench at the measuring position of 100 Nm would then be given as **99.300 ± 2.621 Nm**, with a coverage factor of k=2.

8. Useful references

1. ISO 6789:1992 Assembly tools for screws and nuts - Requirements and test methods. www.iso.ch.
2. EA-4/02 – Expression of the uncertainty of measurement in calibration.- www.european-accreditation.org
3. EA-10/14 – EA Guidelines on the calibration of static torque measuring devices.
4. 6th EU Framework Research Program - www.cordis.lu
5. Feanor OÜ, Tallinn, Estonia – www.feanor.com
6. PQ Systems Inc., Miamisburg OH - www.pqsystems.com
7. L&W, Dresden, Germany – www.lw-gmbh.com
8. Rahsol Dremotec, Remscheid , Germany – www.gedore.de
9. Prore, Milano, Italy – www.prore.it