TCal: Contribution to metrology for Industry 4.0

Sasho Andonov1 and Marija Cundeva-Blajer2

1 PhD student, Ss. Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies-Skopje, Ul. Ruger Boskovic, br. 18, POB 574, 1000 Skopje, R. North Macedonia
2 Ss. Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies-Skopje, Ul. Ruger Boskovic, br. 18, POB 574, 1000 Skopje, R. North Macedonia

E-mail: sasho.andonov@t.mk; mcundeva@feit.ukim.edu.mk

Abstract. Touchless Calibration (TCal) is introduced as a future development in calibration metrology. TCal is dealing mostly with decreasing the steps necessary to provide calibration traceability. Missing steps actually contribute to considerable decreasing of time and costs of calibration keeping the calibration traceability on high level. In the scope of Metrology for Industry 4.0, it could be one of the important improvements bringing increased effectiveness and efficiency for manufacturing industry. In this paper, the detailed explanation of overall process is provided.

1. Introduction

Touchless Calibration (TCal) is the manufacturing answer of the question: Why to send an instrument to laboratory for calibration? TCal is a concept in which the manufacturers can just be digitally connected to the calibration laboratory, receive a calibration data from the calibration lab and do the calibration in own premises. All this is achieved under umbrella of Industry 4.0. As a basis of metrology, calibration must follow these initiatives and TCal is a contribution to the efforts to provide effective and efficient Metrology for Industry 4.0. In the paper a detailed explanation of the benefits of TCal and the way how to achieve them is elaborated.

2. Concept of Touchless Calibration

TCal [1] is a concept which applies the Industry 4.0 requirements for fast, safe, accurate and flexible operations. It allows to do calibration of measurement instruments (Units Under Tests – UUT) in the manufacturing facilities, without the traditional necessary presence of the calibration reference standard and UUT in the same premises. In the concept of TCal, the calibration reference standard remains in the calibration laboratory and the UUT stays in its company’s premises (which could be thousands of kilometres away) “without touching” each other. The overall concept is described in figure 1.

As it can be seen from figure 1, there is network connection between two laboratories which is used to communicate digitally the “calibration data” from calibration laboratory to the place where UUT is situated. In TCal, the term “calibration data” has wider meaning than in classical calibration and it comprises the calibration and environmental data. TCal calibration data (containing the figicalibration and environmental data!) are used for simulating a ”same room” calibration. The link between laboratories is one-way oriented with direction from the calibration laboratory and the reference standard...
(Transmitter) to the clients premises and the UUT (Receiver), but it could also be a two-way communication. The communication link is Industry 4.0 Network, but it also strictly depends on the process of transforming the ordinary calibration data into “numbers”.

Similar concept as TCal is already implemented in Global Navigation Positioning System (GNSS). GNSS is consisting of few satellite systems launched for the purpose to provide navigation services to military, aviation, marine, civil societies, etc. The GNSS receivers are using trilaterations to calculate distance (PR - pseudoranges) from different GNSS satellites using speed of radio waves (speed of light). By comparing this position with Earth model, the receivers can calculate real position of the object on or above the Earth surface.

Each of the GNSS satellites (there are approximately around 60 already launched and orbiting) has few atomic (cesium and/or rubidium) clocks which provide to the GNSS receivers a highly accurate time. The GPS can provide time accuracies measured in nanoseconds ($10^{-9}$ or billionths of a second) [2]. From the customer side, each GNSS receiver has its own clock which has no accuracy of the atomic clocks.

The information regarding the time from atomic clocks is embedded into GNSS navigational message and it is used to “calibrate” GNSS receiver’s clock for a short period of time. This short period of time is enough for receiver to calculate the position of the subject. Considering that the GNSS signals are transmitted continuously and navigation messages are periodically part of the GNSS signals, the time information of atomic clocks is periodically presented at the receiver. So, in GNSS receivers, the receiver’s clock is calibrated by an atomic clock from GNSS system. And this is very much similar to TCal: The information of time (in a format of a number!) is sent to reciver to calibrate its own time.

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**Figure 1.** Flow-chart for TCal.

The main point in TCal is conversion of calibration data into “numbers” which can be communicated through the Industry 4.0 digital network. Previously it was presented example for transforming the weight into voltage using the paired piezoelectric sensors made from one piece of crystal.

The selection of the sensor which will transform the calibration data into “number” (embedded into calibration message) is depending from the innovative approach to the particular type of calibration. It is qualified as eligible if the Sensor&Transducer can produce “number” (which is transmitted from Transmitter to Receiver) in the form of time or frequency. This is justified by the following reason: time and frequency transmitted through Industry 4.0 Network can easily be recovered with great accuracy.
from the calibration message on Receiver side. Another benefit from transmitting time or frequency is the fact that their accuracy is superior compared to others quantities.

3. Traceability
Calibration is of no value if the requested traceability of measurements is not maintained. Traceability is defined as a requirement to relate individual measurement results through an unbroken chain of calibrations to any of accepted primary (NMI/BIMP) standards or to the fundamental (or natural) physical constants which values are accepted (or correlated) by renowned metrology institutions [2]. The traceability is one of the calibration characteristics where the benefit of TCal compared to classical calibration can be emphasized. The process of traceability establishment through classical (traditional) and TCal calibrations between the primary calibration laboratory (NMI/BIMP primary reference standard) and the manufacturing company (UUT) is given in figure 2.

**Figure 2.** Traceability through Classical Calibration (above) and TCal (below).

From figure 2 it can be noticed that instead of the usual four steps to maintain the traceability chain during calibrations of company instruments (UUT), the TCal offers skipping of few steps. With TCal the traceability with NMI/BIPM primary reference standards is achieved directly in one direct step.

4. Total uncertainty with TCal
The all steps in classical calibration brought particular value of Type A and Type B uncertainty in the calibration process [3]. The total uncertainty (expressed as total variance - $\sigma^2_{tot}$) for both calibrations (TCal and classical) in general, can be expressed by the formula:

$$
\sigma^2_{tot} = \sum_{n=1}^{k} (\sigma^2_{A_k} + \sigma^2_{B_k})
$$

$\sigma^2_{A_k}$ is Type A uncertainty of k-th step and $\sigma^2_{B_k}$ is Type B uncertainty of k-th step. In the steps presented in figure 2, for classical calibration, k = 4 and for TCal, k = 1.

It must be said here that Type A and Type B uncertainties expressed by variances, will add each other, but Type A uncertainty will be more than 4 times bigger for classical calibration than for TCal. This is reasonable to assume because for classical calibrations there will be 4 steps and each of these steps will have repeated measurements. It is also reasonable to assume that each of the steps will produce 10% bigger Type A uncertainty from previous one. So, if the Type A uncertainty (expressed as variance) for one-step TCal is $\sigma^2_{TCalA}$, than uncertainty for 4-steps classical calibration ($\sigma^2_{CCA}$) will be:
\[ \sigma_{CCA}^2 = \sigma_{TCalA}^2 + (\sigma_{TCalA} \times 1.1)^2 + (\sigma_{TCalA} \times 1.1^2)^2 + (\sigma_{TCalA} \times 1.1^3)^2 \]

\[ = 5.446 \times \sigma_{TCalA}^2 \]  

(2)

The equation (2) is valid under assumption that range of \( \sigma_{TCalA}^2 \) and \( \sigma_{CCA}^2 \) is same. It is clear that TCaI will bring improvement in Type A uncertainties (expressed as variances) approximately more than 5 times compared to classical calibration. If we express difference of uncertainties as standard deviations than taking square root of both sides of (2) will result in:

\[ \sigma_{CCA} = 2.33 \times \sigma_{TCalA} \]  

(3)

The TCaI will keep some of the uncertainties of classical calibration in Type B uncertainty, but it will also introduce new uncertainties, which will show up due to the sensing and conversion of the sensors used. The total new Type B uncertainty (\( \sigma_{TCalB}^2 \)) of TCaI may be expressed by sum of variances of new uncertainties:

\[ \sigma_{TCalB}^2 = \sigma_{ds}^2 + \sigma_{env}^2 + \sigma_{sp}^2 + \sigma_{AD}^2 \]  

(4)

The \( \sigma_{ds}^2 \) is uncertainty caused by difference of sensors characteristics, the \( \sigma_{env}^2 \) is the uncertainty due to (possible) difference of data from environmental sensor on both sides, uncertainty \( \sigma_{sp}^2 \) comes from the speed of communication (valid only for dynamic calibrations!) and \( \sigma_{AD}^2 \) is caused by eventual data errors which A/D and D/C devices involved in the process could introduce to the TCaI process (if they are used for digital communication).

The most critical is uncertainty caused by difference of sensors characteristics (\( \sigma_{ds}^2 \)), because all other uncertainties can be strictly controlled by TCaI concept. Actually, the \( \sigma_{ds}^2 \) uncertainty makes the difference between classical calibration and TCaI.

5. **Uncertainty caused by difference in sensors characteristics (\( \sigma_{ds}^2 \))**

An example, the Voltage to Frequency Convertor (VFC) and Frequency to Voltage Convertor (FVC) circuit will be presented for general illustration of the process of estimation sensor uncertainty (\( \sigma_{ds}^2 \)) in TCaI for voltage calibrations. The TCaI voltage calibration is conducted by using a device (Microchip circuit TC 9401) which can be configured as VFC on NMI/BIPM side and the same type of device can be configured as FVC on UUT side.

To keep the uncertainty Type B caused by difference in sensors characteristics (\( \sigma_{ds}^2 \)) as small as possible, it is necessary that the sensors implemented on both sides to be paired. Whatever convertors are used on both sides, they must transfer “Mirror Image” where Industry 4.0 Network is the “Mirror”. The simple example of “Mirror Image” for voltage calibration by using voltage to frequency conversions (and vice versa) is presented in figure 3.

In figure 3 the VFC is Voltage-to-Frequency Convertor and FVC is Frequency-to-Voltage Convertor. The “Mirror Image” is presented by formula:

\[ V_1 = V_2 \]  

(5)

It necessary means that:

\[ f_1 = f_2 \]  

(6)

because the \( f_1 \) frequency (communicated through Industry 4.0 Network as a number) and \( f_2 \) (which will be generated on UUT side) must be the same (6). Only than the FVC will produce \( V_1 = V_2 \).
To check in advance the possibility of TCal, the theoretical analysis was conducted for VFC and FVC circuits built by using Microchip circuit TC 9401. The theoretical analysis was based on rough manufacturing data for this circuit and pretty pessimistic scenario was executed only for Type B uncertainties.

Figure 3. “Mirror Image” in TCal with VFC and FVC.

The Sensor&Transducer on the Transmitter side is not critical. One of the most critical contributing factors to the uncertainty is deriving from ability of Sensor& Actuator on the Receiver side to produce $V_2 = V_1$. So, based on the information regarding the frequency $f_1$, a frequency generator which will produce frequency $f_2 = f_1$ which will be used by FVC to produce the same voltage $V_2 = V_1$, has to be on disposal. The degree of sensors impairment produces the particular uncertainty which is expected and it can be decreased only by calibration of Sensor&Actuator. The main point is that $\sigma^2_{d_s}$ will be actually uncertainty obtained by this calibration. FVC (Sensor&Actuator) must be calibrated “relative” to the used VFC (Sensor&Transducer) circuit. “Relative” means that there is no standard used for calibration. Having a standard is totally unnecessary to achieve “Mirror Image” with “relative” calibration method given in figure 4.

Figure 4. “Relative” calibration of FVC with VFC.

The DC Voltage Source ($V_1$) connected on VFC input is not of interest because its value is compared to $V_2$ (“relative” calibration!) and only the output of Null Detector ($\sigma^2_{d_s}$) is point of interest. It is significant that the used DC Voltage Source must be with value in the same range as the voltage which will be calibrated by TCal. In figure 4, the adjustment of FVC must produce such a $V_2$, so the difference with $V_1$ to be such a small, that output of Null Detektor is as small as possible.

The output of Null Detector (properly processed and calculated) will be the Type B uncertainty sensors contributing factor ($\sigma^2_{d_s}$).

6. Conclusion

To conduct a comparison analysis of the uncertainties between the classical calibration and TCal as in figure 2 is of utmost importance [4]. It is noticeable that, in case of classical calibration, the contributing uncertainties (expressed as variances) are cumulative and add each other. From figure 2, it can be noticed that TCal could bring benefit only if the total Type A uncertainty introduced by TCal is better than
uncertainties declared by the accredited laboratory reference standard, the industrial laboratory reference standard and the company working standard.

Assuming that each step has same range of contributing uncertainties and the company UUT (production instrument) must satisfy the traceability steps from figure 2, the total Type A uncertainty of classical calibration (expressed through the variance) will be many times bigger than Type A uncertainty of TCal.

The main Type B uncertainty factor in TCal is $\sigma_{ds}^2$. This factor is result of imperfection of the “Mirror” image which must to be provided. Whatever type or method of conversion is used, the accuracy of sensors and convertors must be very high, which means that the Sensors must be calibrated “relative” to each other.

Maybe someone will think that it is a problem to calibrate sensors on both sides. However, it is much less complicated, faster and cheaper to calibrate sensors in manufacturing premises and to send it into NMI/BIMP Laboratory than instrument (UUT). It means that instrument (UUT) will be still available for use in the company premises. Actually, it will not leave the company premises at all.

So, in the case presented here, providing small Type B uncertainty caused by used sensors ($\sigma_{ds}^2$) by “relative” calibration between VFC and FVC will increase TCal calibration accuracy. As one of the big benefits for companies will be the fact that using TCal, the time for UUT calibration will be transferred from weeks into hours.

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