Some considerations about choosing a method for TCal

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***Abstract* – The global trends in testing, diagnostics and inspections in manufacturing industry are strongly connected with development and implementation of Industry 4.0 framework. Two years ago, in the scope of initiative Metrology for Industry 4.0, the general idea for Touchless Calibration (TCal) was presented as a method for remote calibration of instruments in manufacturing industry.**
By implementing the TCal, instead sending the instruments, the companies will send only the Sensor/Transducer to the laboratory. Before that, in manufacturing premises they will provide Relative calibration. It is actually "pairing" (with other words: providing a "mirror image") of the Sensor/Transducer and Sensor/Actuators, without having the particular expensive standard (etalon).
The method of transforming calibration data is actually determining the types and characteristics of Sensor/Transducer and Sensor/Actuators. Choosing a proper method, means not to increase the Type B uncertainties to the values which are comparable to the classical calibration.
In this paper, authors will try to present some considerations regarding choosing a method based on transformation of calibration data into Time/Frequency which can be generated with extremely small uncertainties.

Keywords – TCal, Touchless Calibration, Sensors, Transducers, Actuators.

I. INTRODUCTION

The method of Touchless Calibration (TCal) was introduced on XXII IMEKO Congress in Belfast (UK) in 2018 [1]. The uncertainties between TCal and classical calibration were presented in paper submitted to the Joint IMEKO Symphosium in St. Petrsburg (Russia) in 2019 [2] and the cost-benefit analysis between TCal and classical calibration was presented on IEEE MetroInd4.0&IoT conference in Rome in June this year [3].

From all these papers, the benefit from TCal can be clearly noticed, but this is not a flawless method. So, this is a paper which actually addresses the Type B uncertainties which are strongly depending on choosing a method to transduce the calibration data into message on Transmitter's side (Calibration laboratory) and recreate later the same calibration data from the message on Receiver's side (manufacturer's laboratory).

II. CONCEPT OF TOUCHLESS CALIBRATION

The simplified concept of TCal is explained on Fig. 1.

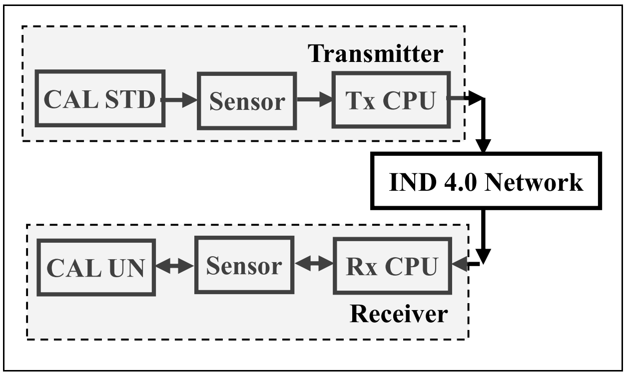

Fig. 1. Simplified flow-chart for TCal

The Sensor/Transducer gathers the calibration data from the CAL STD (which is NMI/BIPM Laboratory Standard) on Transmitter side and particular transducing into another quantity is executed. This quantity is something which can be embeded into digital message which will be used on Receiver side (the manufacturing company) to recreate the calibration data. The recreated data are used for calibration of the CAL UN (Calibration Unit). So, the Laboratory Standard cannot "touch" the CAL UN which is in manufacturing company's premises.

The gathered calibration data from the CAL STD is associated with particular transducing into another quantity which should be actually voltage or current because it can be easy processed. This quantity must be embeded into digital message which will be used on Receiver side (the manufacturing company) to recreate the calibration data. The recreated data are used for calibration of the CAL UN. As it can be seen, the Laboratory Standard (CAL STD) cannot "touch" the CAL UN which is miles away, in the manufacturing company's premises.

The point is that actually, the Sensor/Transducer and Sensor/Actuator do not need to be integrated as Sensor and Transducer or Sensor and Actuator. In general, Actuator does not even need to exist, because this is dependent from particuar application where TCal is used. If TCal is used to calibrate dynamical systems (especially in manufacturing industries), then Actuator could be very much important part of calibration process.

Again, on Fig. 1 is presented the general simplified diagram how TCal should look, but not necessary all parts need to be present. Of course that for the calibration of quantities which are significantly dependent on environmental conditions (pressure, temperature, humidity, etc.), there is need to provide environmental conditions gathered from inside the calibration laboratory and adjust them into the manufacturer's laboratory. In such a case there is need for additional devices [1],[2] which will provide "same room conditions" calibration data.

III. NOVEL UNCERTAINTIES INTRODUCED BY TCAL

The total uncertainty [4] for TCal calibrations in general (similar to the classical calibration) (expressed by variances) can be presented by the equation (1):

$$\sigma_{TCal}^2 = \sum_{n=1}^{k} (\sigma_{TCalAk}^2 + \sigma_{TCalBk}^2) \quad (1)$$

σ_{Ak}^2 is Type A uncertainty of k-th step and σ_{Bk}^2 is Type B uncertainty of k-th step. Looking form on Fig. 1, it is clear that for TCal, k = 1 for Type A uncertainties and k for Type B uncertainties depends on a chosen method.

Our interest are Type B uncertainties because these are uncertainties which are connected by the imperfection of the measurement system. For the sake of the accuracy of presentation, it must be mentioned that the Type B uncertainties present in classical calibration will exist also in TCal, but the values of these uncertainties will be considerably smaller. Reason for that is that these unceratinties, similar to the Type A uncertaities, will be apllied to less steps [2] and their total value will be smaller.

In general total TCal Type B uncertainties can be expressesed [2] as:

$$\sigma_{TCal\,B}^2 = \sigma_{TCC\,B}^2 + \sigma_{TCal\,novel}^2 = \sigma_{TCC\,B}^2 + (\sigma_{ds}^2 + \sigma_{env}^2 + \sigma_{sp}^2 + \sigma_{AD}^2) \quad (2)$$

As it can be noticed from (2), due to introduction of the three additional factors (Sensor/Transducer on Transmitter's side, Industry 4.0 Network in between and Sensor/Actuator on Receiver's side), the TCal will introduce in additiuon, few novel Type B uncertainties. So, in genera, Type B uncertainties for TCal in total, will be bigger. That is the reason that we must take care for all novel uncertainties introduced by these three factors to be kept as low as possible.

The novel Type B uncertainties (their variances!) can be presented [2] by the equation (3):

$$\sigma_{TCal\,novel}^2 = \sigma_{ds}^2 + \sigma_{env}^2 + \sigma_{sp}^2 + \sigma_{AD}^2 \quad (3)$$

The parameters in the equation (3) are:

- σ_{ds}^2 is uncertainty caused by incapability of the chosen method to provide "mirror image" of Sensor/Transducer and Sensor/Actuator characteristics. This is actually the bigest contributor to TCal novel uncertainties and it will be considered in details in next paragraph.
- σ_{env}^2 is the uncertainty due to possible difference of environmental conditions data on both sides. TCal in its general configuration provides also the environmental conditions data for the measurements where temperature, pressure or humidity can affect the accuracy of calibration. For the purpose of this paper it will not be exlained in details;
- σ_{sp}^2 comes from the speed of communication which can be supported by Industry 4.0 network. TCal use is for manufacturing industry and as such it can take into consideration the dynamics of themanufacturing processes which are controlled by some instrumentation. This Type B uncertainty will be valid only for calibrations of instruments needed for dynamic process control and it will not be expained in deatails here; and
- σ_{AD}^2 is uncertainty caused by eventual errors which analogue to digital convertors (ADC) on Transmitter's side and digital to analogue convertors (DAC) on Receiver's side, involved in the process could introduce to the calibration process. As general concept, TCal could also provide calibration for instrumentation used for measurement of analogue quantities (old equipment). It is known that Industry 4.0 is digital platform for communication and as such it will need digital signal to be transferred. So, the change of analogue data into digital data by the use of ADC and DAC is necessity. The biggest error which can happen due to digitalization of analogue output of Sensor&Transducers in TCal, is the quantization error. More bits will gain better accuracy, so, choosing a 24-bits converter [5], [6], will provide relative error equal to 0.06 x 10^{-6} for 10 volts full scale. As it can be noticed, the range of this error is same as the range of Josephson voltage standard uncertainty. Other errors can show up due to temperature drifts, but there are A/D (D/A) devices which have temperature sensor inside (as 24-bits Texas Instruments device ADS 1226 [6]), which are used to compensate the temperature drift. So, the errors triggered by temperature drift are

not significant if such a A/D (D/A) device is used. That is the reason that this uncertainty is assumed to be neglectable.

Having in mind all these notions, it can be stated that equation (3) could be written as:

$$\sigma^2_{TCal\ novel} \approx \sigma^2_{ds} \quad (4)$$

IV. UNCERTAINTY CAUSED BY INCAPABILITY TO PROVIDE "MIRROR IMAGE"

As mentioned in previous paragrpahs, the most important thing regarding the TCal is that the method which is chosen must provide "a mirror image" (Fig. 2).

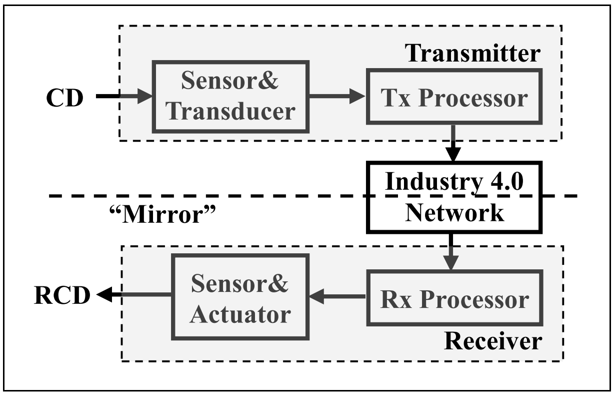

Fig. 2. "Mirror Image" for TCal

Whatever the used method for TCal is, the "mirror image" [2] means that Sensor/Actuator and Rx Processor on the Receiver's side of Fig. 2 must be image of Sensor/Transducer and Tx Processor on the Transmitter's side of the Fig. 2. With other words: Whatever the processing of calibration cata (CD) is applied on the Transmitter side, the inverse processing must be applied to the Receiver side to provide accurate recreated calibration data (RCD) or expressed by formula:

$$\mathrm{RCD} = \mathrm{CD} + \sigma_{\mathrm{ds}} \quad (5)$$

Providing "a mirror image" must be tested (and adjusted!) by Relative calibration (Fig. 3) [2] [7].
Using Fig. 2 and Fig. 3, the uncertainty σ^2_{ds} (in this case expresed as standard deviation [7]) can be presented by following formula:

$$\sigma_{\mathrm{ds}} = \mathrm{RCD} - \mathrm{CD} \quad (6)$$

So, the Relative calibration is needed to provide "pairing" between Sensor/Transducer and Sensor/Actuator which is main condition to recreate the calibration data on Receiver's side ("mirror image"). The possible differences in the "pairing" can be mesured by the Null Detector and they can be used as stadard deviation of variance σ^2_{ds} (Fig.3).

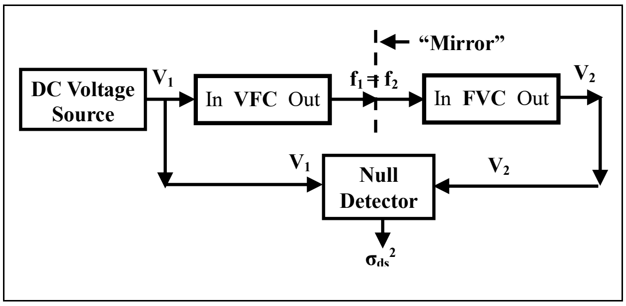

Fig. 3. Relative calibration for TCal

The "pairing" during Relative calibration will be achived by producing same input/output characteristics for Sensor/Transducer and Sensor/Actuator. There the diagram of "pairing" the input/output characteristics for Voltage-to-Frequency Convertor (VFC) and Freqency-to-Voltage Convertor (FVC) [2],[3] is presented on Fig.4.

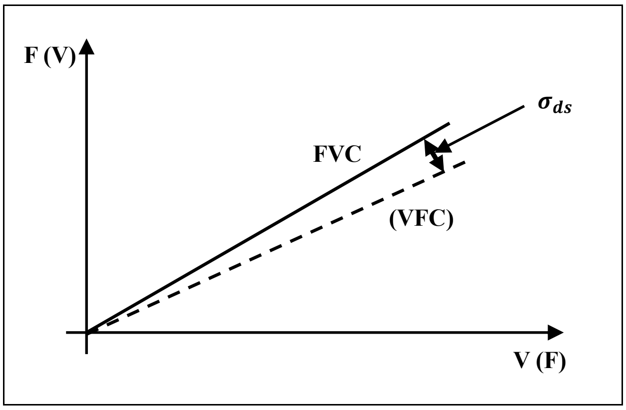

Fig. 4. Adjusting input/output characteristics for VFC and FVC for voltage TCal

As it can be seen, the σ_{ds} is not constant and as the range of calibration is exteding, so the σ_{ds} will increase also. That is the reason that input/output characteristics of the devices must be adjusted and it can be achieved only by Null Detector used in Realtive calibration.

V. CHOOSING A METHOD FOR TRANSDUCING CALIBRATION DATA FOR TCAL PURPOSES

Principle of working for TCal is: Instead to send the instruments to the laboratory for calibration, the calibration laboratory will send to maunfacturer's laboratory the calibration data and there, thes data just needs to be recreated. But this "recreation of data" on the Receiver's side (manufacturer's laboratory) is the biggest issue!

Calibration data will be "sensed" by Sensor/Transducer and there it will be transduced into quantity which must be in such a form to be recreated in manufacturer's laboratory to provide calibration. There are two important characteristics when looking the appropriate method for TCal:

A. Chosen method for transformation (transducing) calibration data needs to have considerably smaller uncertaity (at least 100 times!) than expected uncertainty of the quantity which needs to be calibrated; and

B. Chosen method (presented by type of Sensor/Transducer and Sensor/Acuator!) needs to be easy produced on Transmitter's side and easy reproduced on the Receiver's side.

A. Smaller uncertainty

It is wise if we choose to transduce calibration data into quantity which will have considerably smaller uncertainty then the calibrated quantity. The uncertainty σ^2_{ds} from equations (2), (3) and (4) can be expressed as:

$$\sigma^2_{TCal\ novel} \approx \sigma^2_{ds} = \sigma^2_{ST} + \sigma^2_{I4.0N} + \sigma^2_{SA} \quad (7)$$

where σ^2_{ST} is uncertainty introduced by Sensor/Transducer on Transmitter side, $\sigma^2_{I4.0N}$ is uncertainty introduced by Industry 4.0 Network and σ^2_{SA} is uncertainty introduced by Sensor/Actuator. It is clear that all these three uncertainties need to be small to contribute to the TCal effectivness. If they are at least 100 time smaller then the equation (2) will be transformed into (8):

$$\sigma^2_{\mathrm{TCal\ B}} = \sigma^2_{\mathrm{TCC\ B}} + \sigma^2_{\mathrm{TCal\ novel}} \approx \sigma^2_{\mathrm{TCC\ B}} \quad (8)$$

So, let's try to see from Table 1 what are the uncertainty in measurements for different quantitities in different industries [8]…

Table 1. Uncertainties of different standards for quantities in industry

Quantity	Uncertainty	Best Available Method	Method used in Manufacturing Industry
Length	10^{-12}	Laser Measurements (Accurate, but very expensive!!! Not applicable in manufacturing industry).	Measurement of length in retail manufacturing industry is done by calipers and uncertainty there is in range of 10^{-4}.
Time	10^{-15}	Use of atomic (cesium and rubidium) clocks (expensive, but if GPS satellites and Radio Clock Transmitters are used achieve uncertainty will be 10^{-12}).	Frequency generators avaialbale on the market can achieve accuracy of 10^{-6} and frequency meters of 10^{-8}.
Force	10^{-3}	In the case of forces between 30 – 50 MN. For smaler forces (10 $^{-5}$ MN) only 10^{-2}.	In this areas, the measurement instruments provide uncertainty of 10^{-3} [9].
Electrical Quantities	10^{-8}	In the best case, this uncertainty applies to voltage measurements.	Most of the calibration laboratiries for industry could provide up to 10^{-6}.
Ionization Radiation	10^{-7}	The best case scenario for gamma ray radiation.	For industry and hospitals, the uncertainty can be 10^{-2} (best available personal instrument!)
Temperature	10^{-5}	The best case scenario in different industries.	For mercury termometer (industrial purposes!) the uncertainty is 10^{-1} °C [10].

The Table 1 presents the best case scenarios for the standards in primary laboratories, but for industrial measurements, the manufacturer's companies cannot always afford themselves such an uncertainties. It is clarified in the last column of Table 1. The main point with Table 1 is that these are just aproximately values. Actually, calculating of accurate values is pretty much complex process for all ranges and all purposes of the measurements, so the values inside Table 1 should be accepted as general numbers. For any specific purposes in particular industry, there is need for additional resarch of the available literature.

Let's say, there is company which is producing products where dimensions are important. And let's say, they are producing casings for electronic or telecommunication equipment for retail.

Could such a company afford to have laser instrument for measuring the box dimensions?

The answer is: Maybe, but it will be too expensive! And what is the benefit of that?

Bying such a laser measurement equipment is defying the business logic. In the business and manufacturing industry, there is a simple "rule of the tumb" which is known to every beginner and expert in economy: When the costs of production are going up, the profit is going down. The tolerances for these products in manufacturing industry are 10^{-3} m and why would such a company invest into laser measurement equipment which costs thousands of Euros? Uncertainty of 10^{-12} is needed only for some aplications in some industries (space, aviation, etc.) and even there only particular application requires such an uncertainty of the measurements.

So, nevertheless there are measurement systems which could provide extremely good accuracy and precisions, the companies in manufacturing industry do not need to invest in those systems.

In addition, looking the Table 1, it can be noticed that Time measurements can provide very good uncertaininties. The point is that there are another two benefits of using Time mesaurements:

a) The good (and cheap!) time standards are widely available through satellite navigation (GNSS[1]) and Radio Clock Transmitters; and

b) Time can be transmitted as signal with particular frequency which is actually convinient for TCal purposes.

To be more precise, something very similar to TCal is used in satellite navigation. Actually, satellite navigation is working on this principle:

The GNSS satellites are equiped by one or two atomic clocks (cesium and/or rubidium) and the satellites have embeded into each of its periodically transmiting signal the burst of extremly accurate frequency [11]. The GNSS receiver on the ground is equipped by cheap and inaccurate quartz clock, but by extracting this frequency from the GNSS signal, the receiver use this frequency to calibrate its quartz clock. Due to imperfection of the quartz clock, the calibrated GNSS receiver can keep the accuracy for very short time, but this time is enough to process the signal and to provide navigational information about location with uncertainty of 10^{-8} (for purposes of aviation). GNSS satellites from different consteekkations have different period for transmitting GNSS messages. For example, the GALILEO GNSS signals (messages) are transmitted periodically every 12.5 minutes [12], so the the calibrated accuracy of the quartz clock in the GNSS receiver must be kept for that time.

By using a transducers for TCal which could transduce any quantity (subject of calibration!) into time or frequency could be very benefitial from the aspect of Type B uncertainties.

B. Easy to create and recreate TCal calibration data

Using a time/frequency as method for transducing calibration data is good even from point of view of easy creation and recreation of these quantities. The time/frequency generation and measurement with available time/frequency signal generators and measurement instruments is very good. It can be seen from the last column in Table 1. In addition, the pricess of these instruments are not so high as for Vector Analyser or some other high-tech instrument.

Going further, for implementation of TCal for calibration of the quantities which have uncertainties of the range of 10^{-3} or higher, using time/frequency Sensor/Transducer and Sensor/Actuator can cancel a need for Relative calibration. Simply, having in mind that Frequency Metters and Signal Generators can provide uncertainty of 10^{-6}, the value for σ_{ds} will be 10^{-3} times smaller then required uncertainties, so adjusting σ_{ds} by Relative calibration can be neglected.

In addition, for such a case, there is even no need to send a Sensor/Transducer to calibration laboratory. Simply, the calibration laboratories could provide all necessary calibration information (calibration data and environmental data) to their website and the manufacturer's company could actualy access these data there.

Of course that calibration laboratories need to be paid for these services, but this can be easy achieved, simply by providing User Name and Passwords for the manufacturerer's laboratoris which are willing or have already pre-paid for the calibration services.

VI. USING PIEZOELCTRIC CRYSTAL OR SEMICONDUCTORS TO BUILD SENSORS

Investigation all possibilities to find proper method to implement TCal in reality, the authors investigated a lot of possibilities and one which showed considerable advantage is a use of piezoelectric crystal. The piezoelectric crystal for building Sensor/Transducer on Transmitter's side and Sensor (which will provide Actuator with necessary data to adjust values on calibrated CAL UN, if needed) on Receiver's side has a lot of advantages.

It is well known that piezoelectric crystal [13] has a feature to generate a voltage when a force (strain, pressure, etc.) is applied to it. The generated voltage is proportional to the change of dimensions of the crystal which are

[1] GNSS is acronym for satellite navigation (used in aviation). GNSS is build up by 4 satellite navigation constellations: GPS (USA), GALILEO (EU) GLONASS (Russia) and BeiDou (China). There is no interoperability between these four systems, but GNSS receivers used for aviation purposes should be capable to receive any of these signals and to process them.

proportional (linearly in particular range) to the force applied. This voltage can be measured with considerably small uncertainties (10^{-6}) and as such can be used as calibration information. In addition, the opposite will happen: The piezoelctric crystal will change its dimensions when a voltage is applied.

The benefit of using piezoelectric crystal is that pairing between two crystals for Sensors on Transmitter's and Receiver's side can be achieved with very high accuracy during manufacturing process when Sensors are produced.

The problem is how to transfer this voltage into time/frequency calibration data (information). There is possibility to use Voltage to Frequency Convertor (VFC) on Transmitter side and Frequency to Voltage Convertor (FVC) on Receiver's side, but this solution is not applicable for accurate measurements. Adjusting the "mirror" image between VFC and FVC could be a problem due to difference in linearity of both devices. Anyway, it can be solved by providing more complicated circuits which will be temperature compensated and it could work.

In addition, the semiconductors can be used for some types of Sensors. The semiconductors share the good ability of "pairing" between two devices during manufacturing process. For force (strain, pressure, etc.) measurements, the change of resistance of the seicinductor material can be used. There are already semicinductor's sensors for pressure in aviation, where accuracy is very much important.

VII. CONCLUSIONS AND OUTLOOK

Two most important thing with TCal is to choose effective and efficient method for achieving requested calibration accuracy and precission and to provide pairing between Sensor/Transducer and Sensor/Actuator.

The consideration regarding methods and sensors for TCal in this paper should be used as guidance for the companies which would like to enter this business. There are already considerable production technology for building stable sensors with good accuracy and precission and only additional efforts needs to be put to materialize idea of TCal in different areas.

Using piezoelectric crystals or semiconductors, having in mind advance in these technologies, could give good results to provide sensors which will support TCal.

In general, TCal will bring more economic benefit for manufacturing industry, but there is more research in areas of adapting sensor's technology to needs of TCal. Overall impementation of TCal will need additional efforst from the manufaturing companies as well as from calibration laboratories to adapt their processes to TCal.

Anyway, if this is realised and implemented, the maintenance of the TCal system for calibration laboratories will be very cheap. The benefits for the manufacturing companies are already explained in [3].

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