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ADVANCES IN THE DESIGN OF DMP41 - MEASUREMENT CHAINS USING EXAMPLES WITH TORQUE & MULTI-AXIS TRANSDUCERS

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Abstract:

When evaluating the performance of measuring technology for mechanical quantities based on strain gauges (S.G.), one essential advantage is the possibility to realise smallest measurement uncertainties (MU).

In these applications, S.G. must be able coping with the further tightening of MU budgets. Thus, two advances in the determination of uncertainty of high precision measurement chains based on S.G., are discussed in here. The two uncertainty contributions, what are not always considered so far, are humidity influences and long-term stability.

To support today's sophisticated MU calculations, these two parameters have been further investigated and conclusions are drawn for each of measurement chain elements - reference transducers & precision amplifiers.

Keywords: precision instruments; strain gauges; torque sensors; multi-axis sensors

1. INTRODUCTION

Basically, one can say that mechanical precision measuring chains make use of reference transducers based on the S.G. principle. To achieve a high overall accuracy of the measuring chain, reference transducers -generating only tiny signals- must always be operated together with a precision instrument based on a bridge amplifier [1]. Let us investigate two examples of high precision measurement chains, one with a torque transducer and the other one with a multi-axis transducer, both in combination with the high precision instrument DMP41.

The first example (see Figure 1) shows a typical set up of a torque reference chain at an NMI (National Metrology Institute), the TN Torque Transfer-Standard together with DMP41. TN is especially designed for reference, so non-rotating use, meeting class 0.05 according to DIN ISO 51309, the highest requirement in this field.

The second example shows, the characteristic phenomena, that especially multi-axis transducer requires the processing of 6 signals at the same time. With DMP41 a high precision instrument was developed to comply with the requests of metrologists for fully simultaneous signal processing of a larger number of measurement channels than possible with the predecessors [2].

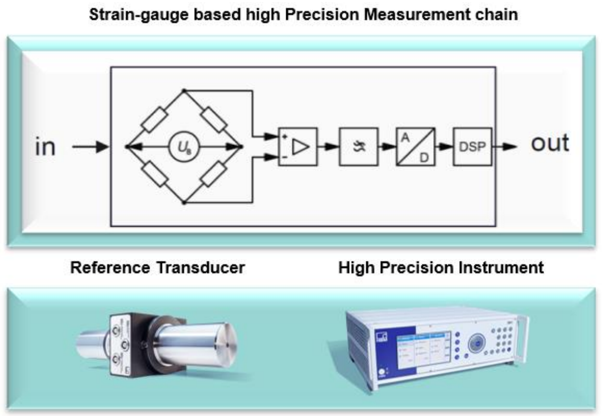


Figure 1: Torque precision measurement chain with TN Torque Transfer-Standard and DMP41

Figure 2: DMP41 can e.g., be used to read out the 6 forces & moments measured by MCS10 multi-axis transducer

Figure 2 shows the use of DMP41-T6 desk top device with the MCS10 multi-axis transducer, requiring the measurement of three forces and three moments, which can now be perfectly taken over by the six simultaneous channels of the high precision device. Together with the background calibration [3], up-to-date interfacing and network integration, this makes the direct evaluation of the results, whether directly on the device, with the client or in the software, much easier [4].

Such high precision measurement chains are also used in Metrological research, especially EURAMET research projects we are involved. These are EMPIR18SIB08 ComTraForce -

"Comprehensive traceability for force metrology services" [5] as well as the most recent EMPIR Torque Metrology project 19EN08 WindEFCY - "Traceable mechanical and electrical power measurement for efficiency determination of wind turbines" [6]. It is clearly noticeable, that in these projects MU budgets are much smaller than before.

2. NECESSITIES FOR REFERENCE TRANSDUCERS

As described in the introduction S.G.-based measuring technique in NMIs is connected to the quantities force, torque and pressure [7]. This paper concentrates on torque as well as multi-axis transducers. If we look to the behaviour of these transducers, it seems that although they are well described with the newest development, there are parameters, which increasingly require attention [8].

One such parameter is humidity: you may conclude, that by the principle used in the transducer, beside of temperature, also humidity needs to be carefully considered as a significant source of uncertainty. Humidity deserves special attention, as "open" strain-gauge transducer designs are known to be influenced by humidity due to the hygroscopic behaviour of carrier of the foil-type S.G. hygroscopic substances accumulate in water. In case of the S.G.s the carrier it also absorbs the water. You may imagine it like a sponge, what sucks the water from the environment.

Unlike quite generally hermetically sealed force transducers, is that for both -torque transducers and multi-axis transducers - there are reasons to realise them as an "open", so not hermetically sealed design. Such reasons, as in case of torque transducers can be their inner structure. To benefit from the advantages of a complete monolithic design, this torque sensor must be designed in the form of a shaft [9]. Realising hermetically sealed sensors using e.g., laser welding is only possible if there are no forces or moments bypassed by this construction.

In the case of TN as Torque Transfer-Standard - to benefit from the advantages of a complete monolithic design, this torque sensor must be designed in the form of a shaft [10].

However, shaft sensors are just an example of the type, what can only be realised as "open" designs, thus they cannot be hermetically encapsulated. Without hermetic encapsulation, foil type S.G. are very dependent on moisture. By optimising the strain gauge carrier, finally the insensitivity to moisture could be significantly improved. It is especially important, as the uncertainty of the whole measurement chain is about the uncertainty of TN, while the uncertainty amount could be minimised and so we put much emphasis on it [11].

One could make the argument that you do not know whether uncertainty contributions are insignificant until you have calculated them [12]. At that point you can still provide evidence by demonstrating by how much they are insignificant. And it is not just about sensors, but the sensitivity of instrumentation to humidity, as opposed to temperature, is not something that one may have seen this in previous publications, it might also be relevant that the humidity control at air-conditioned laboratories tends to have much wider ranges than temperature control, e.g., in several NMIs with large MN deadweight machines air-conditioning over the year has shown humidity changes of several decades of % RH while temperature fluctuates within several degrees kelvin only.

3. HUMIDITY AND ITS UNCERTAINTY CONTRIBUTION

Thus, there is a reason, why digging into the humidity topic is necessary. The resulting change of the mechanical properties of the strain gauges in the Wheatstone bridge, as well as external, additional S.G. for temperature compensation, can affect the S.G. bridges' behaviour. The transducer is exposed to varying humidity levels; it displays a response in both sensitivity and zero signal [13].

To be specific the effect on the zero signal is often much higher than the change in sensitivity, however, most of it can be compensated by taring. Only the relatively small deviation of the zero-signal taking place during the − relatively short − loading process cannot be compensated for by taring and, for its small size can be neglected here. The impact on the sensitivity of the measurement, however, is essential for the uncertainty budget and the outcome of the inter-laboratory comparisons. It is thus essential for usability in inter-laboratory comparisons. For this reason, questions related to environmental stability foil-type S.G. have been asked by several NMIs [14], [15], while some methods have been explained hoe to investigate this influence [16], [17].

4. CREATING GREATER INSENSITIVITY AGAINST HUMITIDY CHANGES

For cases, where it is impossible to encapsulate the S.G., we must think about how such a strain gauge is build up. In fact, it consists out of two main parts, the S.G. carrier, and the measuring grid. The measuring grid out of constantan shows basically no impact to moderate changes in moisture, as it is a suited alloy. A huge influence, however, shows the carrier. Conventionally glass fibre reinforced phenolic resin or polyimide has been used as a carrier material of the S.G.

In recent times another material, Poly-Ether-Ether-Ketone (PEEK) has been increasingly employed, as mechanical and thermal properties have shown to be promising. The stress–strain curves obtained at different strain rate show the viscoelastic effect observed in unfilled PEEK, but by the filled one, called PEEK-F, this is not the case. Having in mind that the elastic properties of PEEK are relatively unaffected at lab temperatures also the dynamic behaviour of PEEK is promising [18]. And above all, PEEK offers an excellent stability against moisture, which is the main reason why strain gauges used for the new TN transducer are based on exactly this carrier material, which ensures their excellent metrological properties – and makes them suitable for transducers with high requirements.

Although relatively new, it has proven to be a very good carrier material for load cells. PEEK is an organic thermoplastic polymer used in engineering applications such as automotive & aerospace, as well as in biomedical applications.

A suitable comparison of different S.G. carriers is to investigate the signal change due to moisture absorption of different strain-gauge carrier materials. As a result, that the signal change due to moisture absorption for totally three types of strain gauges are compared, which are PEEK, polyimide and glass fibre reinforced phenolic resin.

The chart shows maximum values for utilization in a full-bridge design, while only one S.G. is exposed to humidity. Measurements have been taken at a temperature of 50 °C and 95 % relative humidity (RH). It shown that it has a reduced humidity absorption of ~ 0.2 % (compared to 1.1 % - 1.7 % for Kapton and 2.0 % for glass fibre reinforced phenolic-resin carrier material) and, additionally, a quite good resistance against most chemicals. To sum it up, compared to glass fibre reinforced phenolic resin, PEEK carrier material shows significantly lower humidity absorption, at an approximate ratio of 1:6. This is an astonishing ratio.

This carrier material is also quite easy to use during installation and allows small curvature radii, which is important for radially symmetric transducers with strongly curved surfaces. In terms of thickness the used special PEEK S.G. carrier also is much thinner than glass fibre reinforced phenolic resin. Thus, the hygroscopic relevant volume is much smaller.

The carrier's hygroscopic behaviour can again be visualised using the image of a sponge: the smaller its volume, the less moisture can be absorbed. It should be mentioned here that the direction in which the strain gauge is acting can be able to decide to what extent a saturation has consequences. If you imagine the carrier of a strain gauge as a "sponge" that soaks up water, then the measuring grid with different moisture levels is at different levels. The linear gauges as well as "fish-bone" strain gauge can pick up circumferential signals, and this mixed effect makes it impossible it is caused by a real signal or just a change of humidity.

Table 1: Applied strain gauges and measuring direction

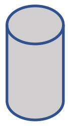
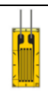
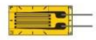
Application of S.G. on measuring body	**Horizontal pick up**	**45° signal pick-up**	**Vertical pick-up**
 with cylindrical shape	 linear strain gauge	 "fish-bone" strain gauge	 linear strain gauge

Table 1 explains the different results for torque and e.g., bending moment measurement. It also explains the different results for the different sizes: Ranges that have a measuring body with a larger diameter and consequently circumference are less affected by moisture than the smaller measuring ranges with a smaller diameter and consequently circumference.

For the TN Torque Transfer-Standard transducer the improvement can be described in an approximate improvement for all new versions (covering the range 100 N·m - 20 kN·m) of typically only < 10 ppm/% RH, while the previous versions in the larger ranges, 2 kN·m - 20 kN·m have shown typically 40 ppm/% RH and in the smaller ranges (100 N·m - 1 kN·m) typically even 60 ppm/% RH. These results are quite impressive, and they may allow to skip humidity as a contribution to MU, even for transducers with open design.

5. PRECISION AMPLIFIERS, COMPARISION DMP41 VS DMP40

All versions of the DMP-series, such as DMP39 and DMP40, as well as the current DMP41 are based on an inductive voltage divider. Such dividers are very accurate because their accuracy is only defined by the ratio of the number of windings. The "digitally" defined ratio of windings allows to realise relatively small deviations of the instrument. This is the basis of their outstanding long-term stability.

DMP41 and before that DMP40 and DMP39 have been the worldwide standard at National Metrology Institutes, standard institutes around the world you can rely on over 5 decades [19]. Exactly 10 years ago, the DMP41 has been introduced [20].

In Table 2 a comparison summarises the discussed DMP41 features compared to those of its predecessor, the DMP40. Outstanding is, that by its patented background calibration, no freezing anymore during internal calibration, but live measurement continuously goes on [21].

Table 2: Basic technical data DMP41vs DMP40

Precision Device	**DMP40**		**DMP41**	
Manufactured	1995 - 2013		2013 until now	
Accuracy class at 10 V excitation voltage	0.005 (50 ppm)		0.0005 (5 ppm)	
Type of voltage divider	inductive		inductive	
Desktop models	DMP40	DMP40 S2	DMP41-T2	DMP41-T6
Simultaneous channels	1	2	2	6
Possibilities for transducer connection	8 × DP15P	16 × DP15P	2 × DP15P 2 × MS	6 × DP15P 6 × MS
Available interfaces	RS232 RS422/485		Ethernet RJ45 USB device 2 × USB host RS232 via USB adapter	
Behaviour during internal calibration	Indicator freezes, live meas. stops		No freezing, live meas. proceeds continuously	
Temperature drift zero (TC0)	< 2 ppm/10 K typical < 1 ppm/10 K		< 2 ppm/10 K typical < 1 ppm/10 K	
Temperature drift span (TCS)	< 5 ppm/10 K typical < 2 ppm/10 K		< 5 ppm/10 K typical < 2 ppm/10 K	
Short-term drift	< 5 ppm/24 h typical < 2 ppm/24 h		< 5 ppm/24 h typical < 2 ppm/24 h	
*Conditions: measurement range 2.5 mV/V, transducer resistance 350 Ω, cable length < 10 m				

With DMP41 we have the choice of a precision instrument with a pleasingly small measurement uncertainty [22], [23]. This makes it possible to set the goal to keep the total measurement uncertainty of the whole measurement chain approximately close to the uncertainty of the reference sensor [24].

The prerequisite for this is that really all the MU contributions of the amplifier must be very small. We will look in this in the next two sections.

6. QUANTIFICATION OF INFLUENCE OF HUMIDITY ON INSTRUMENTS

So far detailed moisture sensitivity information primarily has been provided only on some transducers, and not on amplifiers. However, as NMI projects show [25], that with the measurement uncertainty budgets getting smaller and smaller, it is necessary to investigate also on electronic instruments, as these effects are presently widely unknown. Prediction and control of humidity effects has not been possible, but only to make assumptions about the loads that will affect an assembly during its entire service life. For long such problems, e.g., that assemblies are often prone to electromigration due to condensation on the flux are discussed [26]. A review of the factors influencing the reliability of electronics is given in [27]. There is humidity interaction with materials and ionic contamination on the PCB surface. This type of corrosion on the PCBs is commonly referred to as creep corrosion.

Of course, precision devices must be considered separately, since even the smallest deviations are important here. Formerly NMIs reported that the “stability of BN100A, as bridge calibration unit, was verified under altered air humidity”, while DMP40 (the predecessor of DMP41), still seemed to show a “slight linear trend line with increasing humidity or temperature”.

It demonstrated that precision electronics are also influenced by humidity, and, in terms of precision electronics plays an important role. Therefore, the so-called “climate safety of electronic assemblies” has been research topic in several applications for decades [28]. It was found that, apart from incorrect measurement results, error images such as electrochemical migration, leakage currents, flashover, solder joint load, and corrosion may occur.

In any case, in the development of precision instruments close attention must be paid to this point. This is true in the selection of electronic components, but also in such factors as the instrument’s inner voluminal and even in the housing design, such as the general use of metal housings, as due to possible condensation of water at the inside wall the cabinet, the use of metal housing is essential for building up precision amplifiers.

By implementing a whole bunch of measures, the influence of humidity on DMP41 could be reduced by more than a full decimal place (see Table 3).

Table 3: Technical data of the DMPs regarding humidity influence

Precision Device	Humidity Influence
DMP40	typically < 0.6 ppm/% RH
DMP41	typically < 0.04 ppm/% RH

7. LONG-TERM STABILITY

Even if the long-term stability MU contribution is comparable small, knowing its importance in measurement, for the DMP series it has been measured since the introduction of the first device of the DMP series in 1980 up to the latest measurement just in this year. Doing so, the long-term stability of this valuable first devices, switched together to a high precision measurement chain, consisting out of a BN100 with serial number # 010 an the very first DMP39 with serial number # 001, has been monitored by internal calibration method. Figure 3 shows now the results regarding long-term stability, meaning, for the entire period of now 42 years, the whole measuring chain does not leave an error band of ±2.5 ppm.

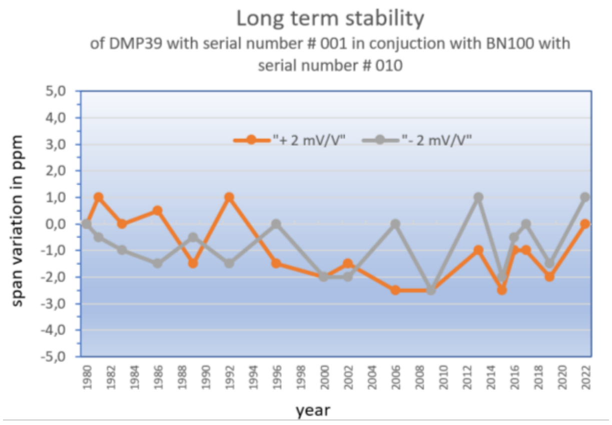


Figure 3: Long term stability of DMP39 #001 & BN100 #010 from year 1980 to year 2022

In fact, such an outstanding long-term stability cannot be further improved, so that the same values can be concluded for DMP41 and DMP40 (Table 4).

Table 4: Technical data of the DMP41 vs DMP40 regarding long-term stability

Precision Device	Long-term Stability
DMP40	< 5 ppm/yr typical < 2 ppm/yr
DMP41	< 5 ppm/yr typical < 2 ppm/yr

8. SUMMARY

Traceability in nearly all mechanical laboratories of NMIs depends on highly precise measurement chains with bridge amplifiers based on the S.G. principle. It could be shown that requirements to precision electronics can be set even higher than to reference transducers.

To quantify this, S.G. high precision chains (also called reference chains) consisting of a sensor and a precision amplifier usually both must be investigated to find out the biggest contributors to MU in each of them and finally to the MU of the whole chain.

If we look to the behaviour of reference transducers as well as precision instruments, it seems that although they seem well described, there are parameters, which are increasingly attracting attention. Therefore this article has been dedicated to humidity dependence and long-term stability investigations.

The approach to follow, is to look the precision measurement chain's MU as a whole and then decide for which part we must consider further MU contributions. In other words, we must decide they have to be included or neglected. These decisions - what to include in the MU calculation - must be done responsibly and with sufficient knowledge.

On the transducer side, a reduction of humidity sensitivity due to the use of a less hygroscopic material also allows shortening the above-mentioned time of sufficient "balancing" before starting the measurement. The necessity has been repeatedly noted by several NMIs. This article now provides estimations on this effect in terms of the created MU in ppm/% RH.

On the precision amplifier side, the DMP41 justifies expectations placed on it and assists necessary MU budget minimisation. By its accuracy class - a manufacturer's term - but also by its real MU behaviour, such as the amplifier's outstanding long-term stability, based on measurements over decades, are hoping to help NMIs to focus on the very research subjects, as you may trust the unchangeability and stability of the instrument.

The presented research is hoping to contribute to metrological traceability. After merger of Hottinger Baldwin Messtechnik with Brüel & Kjær Sound & Vibration to now HBK - Hottinger Brüel Kjaer, the company is supporting metrology with an even wider scope [29].

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