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A novel type of precision amplifier for strain gauge based transducers

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Abstract −If accuracy matters, mechanical quantities such as force, torque or pressure are almost exclusively realized by transducers, which are based on strain gauges. To exploit the potential of static measurements the demands on precision amplifiers steadily grow. This paper gives some details to progress of the precision amplifiers used.

Keywords – **strain gauges, traceability, amplifier**

I. INTRODUCTION

Strain gauge precision transducers are always based on a Wheatstone bridge. By the help of strain gauges (S.G.) arranged in a Wheatstone bridge, mechanical quantities such as force, pressure, torque generating strain can be converted into a voltage (Figure 1).

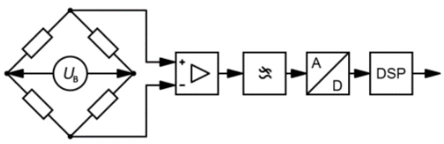

Figure 1 Schematic view of the strain gauge amplifier

This Wheatstone bridge is necessary, as the pure change of resistance is far too small. However the unbalance of the Wheatstone bridge, comparable to a double voltage divider allows an output signal of nominal 2 milliVolt per Volt (mV/V) excitation voltage U_B.

The excellent read-out of the signal benefits from two main principles used in the instrument, which should be briefly explained here as they are the basis for the latter chapters.

In the elastic deformation range of materials the methods of calculating the material stresses from the measured strains are based on Hooke's Law. In its simplest form for uniaxial stress state Hooke's law is [1], [2]:

$$\sigma = E \cdot \varepsilon \quad (1)$$

with

σ = material stress
E = modulus of elasticity of the material
ε = strain.

The variation of resistance is defined by

$$\Delta R/R_0 = k \cdot \varepsilon \quad (2)$$

with

ΔR = change of resistance
R_0 = basic resistance
ε = strain
k = gauge factor.

This bridge can be extended by useful outer circuitry to "trim" the transducer. For instance zero-point, linearity as well as the temperature compensation of zero point (TC_{zero}) and span (TC_{span}) [3], [4] can be changed (Fig. 2).

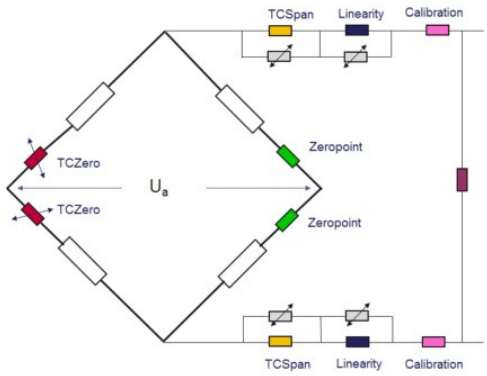

Figure 2 Internal wiring of a precision force transducer

The bridge can be supplied by DC or better AC as a "carrier" (frequency fc). Now we have to distinguish in between the frequency of the carrier and those of the measuring signal. The mechanical quantity changes with the signal frequency.

Precision measurements are carried out preferably at f_c equal 225 Hz and voltage conditions of 2mV/V. The frequency of 225 Hz has been chosen by many National Metrology Institutes (NMI´s) around the world, as it is no multiple of the disturbing 50 Hz or 60 Hz power supply.

At the same time it allows a bandwidth suitable for measurement processing of static and quasi-static signals.

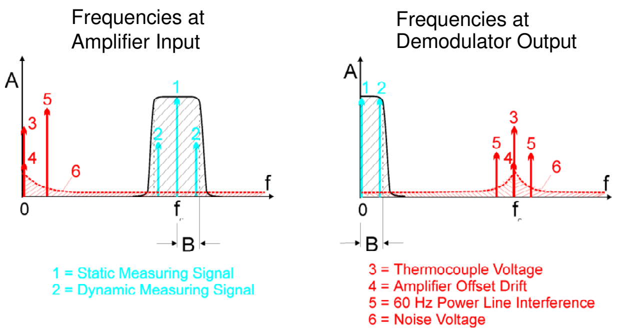

Figure 3 Input and demodulator frequencies in using carrier frequency principle

Another reason is that it keeps the influence of noise low. In figure 3 the spectra of the used carrier frequency principle can be seen. In the graph on the left side the dotted line 6 describes the noise voltage. At 1/f noise function the choice of 225 Hz ensures, that one is definitely in the degreased noise, so above the area of significant noise, which occurs close to 0 Hz.

II. RELEVANCE OF THE TOPIC

Traceability of mechanical quantities is relevant to many fields of industry. To name an example, torque measurement is essential for power as well as efficiency measurement and thus to the degree of carbon monoxide pollution and nitrogen oxides in the air. The same is true for force transducers, who e.g. in combination with actuators, are components for all kind of test stands [5].

Another example is the use of pressure transducers as altimeter in aircrafts, so in an in-flight application. Flight authorities often carry out inter comparisons using HBM calibration equipment such as the DMP precision amplifier series.

In calculating uncertainty of the whole measuring chain using HBM precision amplifiers you will notice, that the overall uncertainty of the measuring chain is often required to be very close or at least in the range of the measurement uncertainty of the transducer itself.

To safeguard critical applications the quality and performance of any kind of calibration equipment is getting more and more important [6], [7], [8].

Due to its worldwide need metrological applications are the most important application fields of precision measurement. In metrological applications one uses the term "calibration pyramid", expressing that the precision of the measurement should correspond to the level of calibration needed.

Our company has taken part in numerous EURAMET driven metrology projects, in various research fields such as MN forces, MNm torque values as well as the subject of the challenge of dynamic calibration, all to be understood as basic research in the field of metrology of mechanical quantities [9], [10].

III. THE NEW MX238B MODULE

This section gives scope for explaining the way we went in developing a new type of precision amplifier for strain gauge based transducers.

Despite we have been able to build amplifiers "on the physical limit" down to an accuracy of 5 ppm as early as 1981 (birth date of DMP series), for a better traceability of mechanical quantities in industrial applications; there is also the requirement of building up measuring chains of a total uncertainty of "only" 100 ppm.

This total uncertainty should not be evenly distributed to transducer and amplifier, but the requirement to the amplifier is significantly better, so we put 25 ppm as our goal.

This idea was set by HBM already a long time ago, and created some series of models with "...38" in their name, such as DK 38 introduced in 1982, ML38 introduced in 1995 and ML38B introduced in 2005.

This way HBM was creating its own class of legendary precision amplifiers. During the years the seemingly constant demand for an accuracy of 25 ppm has actually become an increasingly higher requirement, as the requirements of the electromagnetic compatibility over all the time steadily increased.

Of course miniaturization and compact size per channel is a requirement of many calibration applications. In most calibration applications two channels have to be compared ("actio = reactio"), e.g. a reference force transducer and a specimen pressed on each other in a deadweight or hydraulic force calibration machine.

Thus a new amplifier module should feature two independent (simultaneously measuring) amplifiers, each of the channels offering an accuracy class of 0.0025 (25 ppm). This is realized by using a 24-bit A/D converter for each of the amplifier channels.

This new module should be called Quantum MX 238B belonging to the QuantumX family and referring to the above mentioned famous models with "…38" in their name.

Fig. 4: The new amplifier module for any kind of strain gauge transducers Quantum MX 238B

It is based on the principle of carrier frequency (CF principle), what has several advantages to be discussed here: The advantages are mainly in the insensitivity to interference and thus a higher quality of measurement. In the result the use of a carrier frequency allows a much better signal to noise ratio. HBM, as described in the previous chapter, also for the reason of good traceability back to the national standard, is using a carrier frequency of 225 Hz for this new amplifier as well [5].

Hereby the transducer is fed by a sinus-wave voltage and works therefore like a modulator. Details of this can be reviewed in [6], [7], [8].

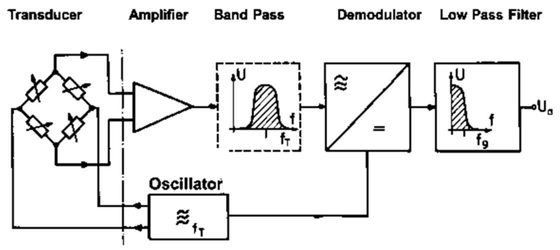

Figure 5. HBM High Precision Amplifiers are based on carrier frequency principle (CF)

A further interesting feature is the automatic channel parameterization by TEDS (Transducer Electronic Data Sheet), a technology that allows you, to plug in sensors and get started, as a self-recognising process. The characteristics of a transducer are stored inside as an electronic data sheet. The amplifier can import these data.

It then converts it automatically into the right settings and gets on with measuring straight away, in the correct units, with no further effort on the customer side. It basically allows you to just plug in and get started and significantly simplifies the handling of sensors. Generally, TEDS can be mounted in the sensor housing or in the plugs of the transducer. When TEDS is mounted in the plug, it should stack with the transducer, preferably with a plug mounting from HBM [10].
For a schematic block diagram of MX 238B, see Fig. 6. It is belonging to the HBM QuantumX family, an amplifier family what allows you to process nearly any kind of signal, for instance with the MX840B module what supports as much as 15 different transducer technologies. Module MX410B is also a suitable amplifier for dynamic calibration as it can be seen in [12]; [13].

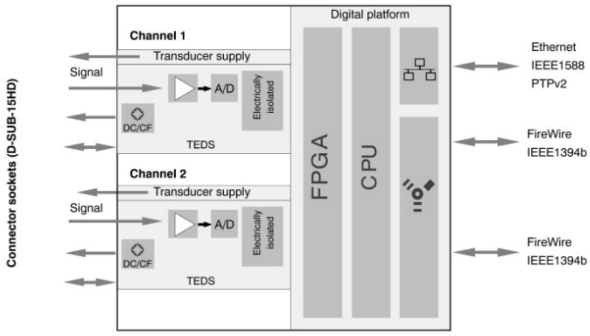

Fig. 6. Schematic view of module Quantum MX 238B

With the introduction of this module QuantumX offers the ability to process and display multiple signals of very different accuracy-bandwidth combinations at the same time. This is one essential advantage of the fact, that MX238B is member of a big family of modules, the HBM main product family QuantumX.

The existing diversity of modules reflects the wide range of measurement tasks, such as needed on test rigs, to perform efficiently with QuantumX by covering many different measurement principles and aspects.

Now the user can choose from a number of modules, namely QuantumX MX238B, QuantumX MX430B, QuantumX MX840B, and QuantumX MX410B in fine steps of very different accuracy-bandwidth combinations, depending on the real needs of the specific measuring task.

All these modules can be connected by IEEE 1394b FireWire and synonymous measurement (in the range of 1 µs) is supported by PTP (precision time protocol) v2.

First time in HBM history we are using a using a hermetically sealed resistive divider. This component is already very good on its own. However we decided to still implement active temperature compensation.

This additional active temperature compensation is further reducing the already very low temperature coefficient to close up the gap to inductive dividers. This advantage comes with the advantage of miniaturization. Now HBM can offer such a dual-channel module at the same time as compact as this is necessary and possible for a realization in the QuantumX family.

Despite of or even because of using a hermetically sealed resistive divider as a reference, one of the outstanding features of the new amplifier is its fantastic independence from temperature for both of the relevant values, so concerning the temperature drift of the zero point and the temperature drift of the span. For details please refer to below table 1.

Precision Device	DMP41	ML38B	MX238B
Voltage Divider	inductive		resistive
Temperature drift zero	< 2 ppm	< 10 ppm	< 5 ppm
Temperature drift span	< 5 ppm	< 20 ppm	< 10 ppm

Table 1. Comparison of temperature drift of different amplifiers

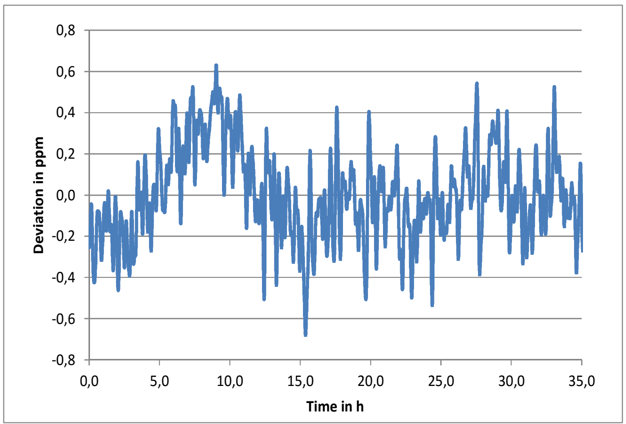

Fig. 7 Short-term stability of Quantum MX238B: Measuring with activated Background-Calibration (2.5 mV/V @ 5.0 V rms)

The idea of background calibration, first used in DMP41 ([14];[15];[16]), also has been implemented into Quantum MX238B. As you can see in Fig. 7, the short-term stability of Quantum MX238B has been measured. Fig.7 illustrates a measurement plot of a 2 mV/V signal over 35 hours, where a background-calibration was triggered every minute. During the measurement many such background calibrations are performed. Different use cases have shown that this method has no negative or disturbing influences. The adjustments of the background calibration cycles are in the sub-ppm range. Only the constant thermal noise of the sensor and mainly the voltage noise of the amplifier are recognizable. There are not any interferences visible in the noise floor. Thus this demonstrates that is now possible to calibrate during measurements without any interruption.

Deactivation of the background-calibration does not improve the accuracy, but it will even worsen the accuracy. The user does no longer have to worry about the active control of the previous auto-calibration to get no interruption when measuring.

As the short term stability is excellent we suppose long-term stability also to be very good, however for this just introduced device, so far, there are no measurements available. First we have specified < 0.0015 %/a with “Auto calibration On” to be on the safe side and will follow up this over the next years.

Possibly we will be able to improve this value again after some time, as we will monitor long term stability the same way, as we have done for a measuring chain consisting out of BN100 and DMP39 for approx. 35 years (details see next chapter).

IV. FACTORS FOR THE RELIABILITY OF THE MEASURMENT

In this chapter the following topics, as they are considered important factors of reliability of the measurement, should be discussed.

These are:

a) Traceability
b) (Long term) stability
c) Referencing the measurement to a standard
d) Ensuring reliable measurement.

First of all traceability is a must. Primary calibration is the highest level, carried out by the national metrology institute. Thus metrological applications realize chains of traceability linking measurements made in practice back to reference standards. Such standards are realized by HBM reference transducers and highest precision instruments.

This core concept in metrology - metrological traceability - is supported by the outstanding performance of precise products. The main advantages of using strain gauge based technology is that measurement chains offer an extremely low measurement uncertainty at very good long term stability.

This leads to another factor of measurement reliability. It is the stability and beside of the data of Short-term stability data gathered and described in the previous chapter, also for longer periods of time the new QunatumX MX238B measuring amplifier shows very good results.

Device Type	DMP41	ML38B	MX238B
Voltage Divider	inductive		resistive
Initial accuracy	5 ppm	25 ppm	25 ppm
Short term drift (5 min, from 2h after switch on)	2 ppm	10 ppm	better than 10 ppm
	Typ.: 1 ppm	Typ.: 3 ppm	-new device-
Drift over (24h resp. 48h) (%/a)	5 ppm	20 ppm	10 ppm
	Typ.: 2 ppm	Typ.: 8 ppm	-new device-

Table 2. Comparison of different amplifiers in terms of their stability over time

Since the introduction of the DMP device series s in 1981 we continuously observed the long-term stability of the measuring chain consisting out of “DMP39 and BN100“ (on the basis of inductances we built our own BN100 calibration unit, today called BN100A) and can state that over now more than 35 years its span variation for + 2 mV/V and -2 mV/V signals was every time smaller than the accuracy class of 5 ppm (see following figure 8) [17].

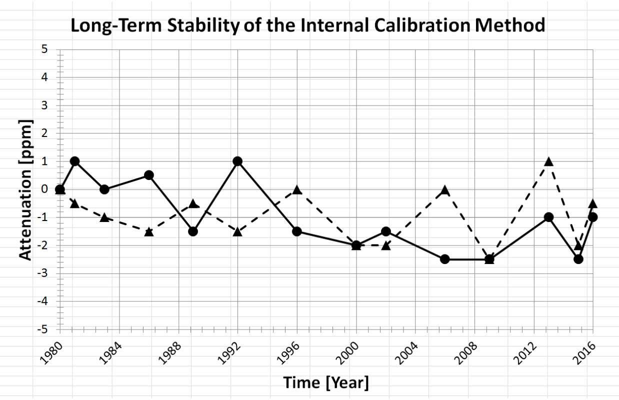

Fig. 8. Long term stability of the established calibration method of a measuring chain consisting out of BN100 and DMP39

For electrical calibration of these measuring amplifiers bridge standards are used, which have to be traceable to national standards.

As a matter of fact, the standards of HBM and of “Physikalisch-Technische Bundesanstalt” (PTB), the German National metrology institute are not same. The reason for this lies in history. HBM needed its own >>Normal<< (mV/ V) to produce first precision amplifiers such as DK37 and DK 38. At that time there was no existing traceability. Then, at the time in 1981, the PTB has set up a normal mV/ V, these normals showed an offset.

As a matter of fact the standard of PTB is technically constructed differently than the normal in HBM; however these values always can be “translated” into each other. In relation to the values acquired by the PTB the end values of all HBM devices with a carrier frequency of 225 Hz, for reasons of continuity, are given 10 ppm lower than the nominal values. There are many articles on the details [18], [19], [20], [21].

MX238B demands the connection of the transducers in a six-wire-connection-circuitry (with two additional sensing lines), as for this class of accuracy the resistance of cable lengths in the range of only cm already counts. Subsequently the device offers also detailed error detection with wire break detection for sensor lines, feeder lines and test leads.

Switchable shunt resistors of 100 Ohms allow an artificial bridge detuning. In a 350 Ohm Wheatstone bridge, so the standard for the strain gauge pickup principle, there is an upset of 0.886 mV / V at 2 mV / V measuring range, i.e. a fairly significant detuning of approximately 40%.

Regarding a more reliable measurement it can be said that the built-in galvanic isolation is a mean to avoid ground loops and therefore the amplifier appears much more robust. Also meeting the high EMC requirements according to EN 61326 for field strengths of 10V/m are a further advantage of the device.

V. CONCLUSIONS

In general the market shows a request that the measured signals can be processed more accurately. In this paper it has been shown, that there is substantial progress regarding compactly build precision amplifiers for strain gauge based on transducers such as force, torque and pressure reference transducers used in metrology.

In fact today also amplifiers based on resistive dividers can perform most tasks with sufficient accuracy. For many decades this was not the case. Due to intensive research, HBM can now offer such a dual-channel module at the same time as compact as this is necessary for a realization in the block structure the QuantumX family.

It is quite certain, that this a previously unknown compactness will open up new fields of integration into applications. QuantumX now offers the ability to process and display multiple signals of very different accuracy-bandwidth combinations at the same time.

Thus the decisive progress realized with the QuantumX MX238B is, that now the cooperation with all the other measurement modules of the product family QuantumX with PTPv2 identical timing, allows data processing absolutely simultaneously. Thus the isochronous bus system (Firewire) allows synchronous processing with many other physical quantities.

The precision measurement module MX238B thus combines the advantages of combination with all QuantumX members with the possibility of taking measurements with an accuracy class 0.0025 (25 ppm). This is achieved by the use of the carrier frequency principle and an applied carrier frequency of 225 Hz.

For the first time here HBM offers its patented background calibration of this precision class. This ensures that the measurement of the two integrated amplifier can be continued without interruption during the measurement, so even during the internal calibration.

Furthermore, the transducer can be recognized with the so-called Transducer Electronic Data Sheet (“TEDS”) and the individual properties of the transducer can be considered and easily red out.

The measurement results have been showing the very good time as well as temperature stability of resistive dividers.

Nevertheless one has to say that the requirements for a top performance, so amplifiers of highest precision for primary calibration purposes, built to operate on the physical limit (such as our DMP-series), further relies on inductive dividers (voltage ratio derived from the number of windings of coils), as they remain still more accurate than any resistive dividers can be.

VI. ACKNOWLEDGMENT

I´d like to thank the contribution of my colleagues Herbert Kitzing and Marco Schäck of the HBM headquarters in Darmstadt; Germany for their valuable contributions.

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