STRAIN GAGE ¼ BRIDGE CALIBRATION WITH SHUNT SIGNALS

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1 INTRODUCTION

In the field of Experimental Stress Analysis hundreds and sometimes thousands of single strain gages are to be measured. Calibration of such big systems can be a tedious task. This paper explains how fast and precise calibration procedures can be carried out automatically by means of simple shunt resistor switching technique.

It is a common technique to use shunt resistors to check strain gage measuring systems. But shunt signals are not considered to be very precise. Their main purpose today is to ensure that everything works properly.

This paper describes that with improved 3-wire and 4-wire technique shunt signals can serve as precise calibration signals. Also in situations where long connection cables with high wire resistances are used and where strain gages have large resistance deviations e.g. due to large pre-strain, the calibration error can be kept below 0.2%.

With the described method the whole system including the wiring of the strain gages can be calibrated without disconnecting the strain gage sensors and replacing them by a calibration standard. So the calibration procedure can be performed fully automatically and very fast.

2 STANDARD CALIBRATION METHOD

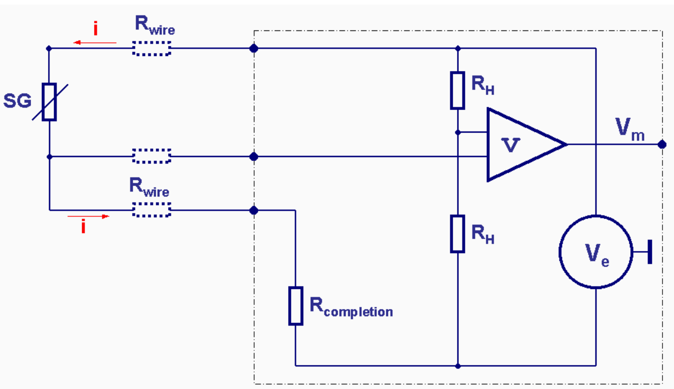

Fig. 1: Standard 3-wire circuit

In most cases strain gages are connected in 3-wire technique as shown in Fig. 1. If the wires and connection contact resistances of outer and inner ¼-bridges stay equal the voltage drops will be the same too and therefore no change of zero signal will occur. But of course the voltage drops across the two current feeding wires reduce the sensitivity of the circuit.

Fig. 2: Configuration with 8-channel calibration unit

Fig. 2 shows an MGCplus 19"-rack with 128 measuring channels (16 amplifier units provide 8 measuring channels each). A calibration unit for 8 channels is placed on top of the MGCplus enabling the calibration of 8 channels at a time.

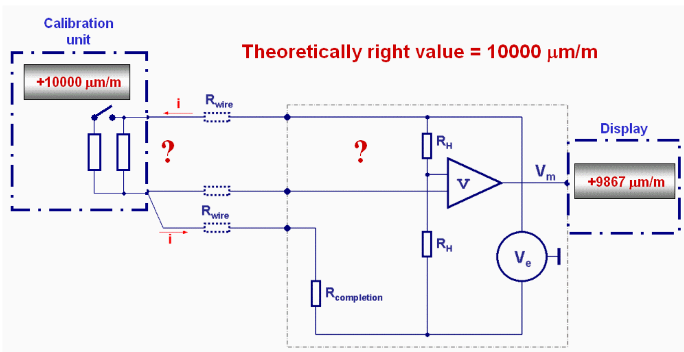

Fig. 3: Calibration chain

Fig.3 shows the measuring chain of one channel.
The calibration unit may be traced to a National Institute of Standard (e.g. NIST or PTB) and therefore provides the signal of 10.000 µm/m as precise as possible. But if the displayed value of the instrument differs from the expected value written on the switch position of the calibration unit (see Fig. 3: calibration unit signal = 10.000 µm/m and display is e.g. only 9.867 µm/m) three different sources may cause this deviation. It may either be a measuring error of the instrument, or it may be caused by voltage drops across the wires, or the calibration unit itself may be faulty. Most probably all three error sources add together.
What we expect to be shown on the display is the value of 10.000 µm/m. This theoretical value of 10.000 µm/m is the real true reference. The calibration unit is already a secondary standard, traced to this true theoretical reference value by the National Institute of Standard.
The objective of the proposal of this paper is to use the calculated absolute true theoretical signal value as calibration reference.
If a precise calibration signal could be induced into the input measuring circle, without disconnecting the strain gage and replacing it by a calibration unit, the calibration could be done by comparing the measured result with the calculated theoretical and really true reference value. A big advantage of such a method would be that all elements of the measuring chain from strain gage through wire- and contact-resistors to the amplifier are included in the calibration procedure.
The calibration then can also be carried out automatically and therefore very fast.

3 AUTO-CALIBRATION / AUTO-ADJUSTMENT

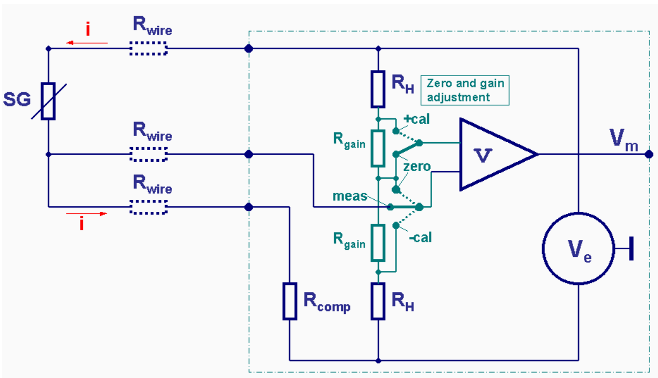

Fig. 4: Automatic zero and gain adjustment

Before the shunt calibration method is adapted an auto-calibration and auto-adjustment procedure may be used to improve the accuracy of the amplifier itself. Fig. 4 and Fig.5 show how to do an auto-calibration procedure. The measuring signal is switched off and zero and calibration signals are switched to the amplifier input sequentially and measured. By doing this the amplifiers zero and gain errors can be corrected as shown in Fig. 5 by some simple calculations provided by a micro computer (µC).
When auto-calibration is used the only characteristics amplifier circuits must provide are good linearity and short term stability between the auto-calibration cycles.
The accuracy of the complete amplifier then is only defined by the precision of the reference divider for the calibration signal.

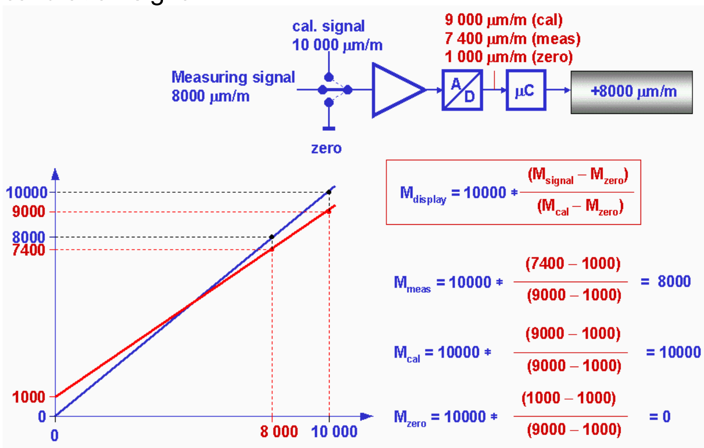

Fig. 5:
Zero and gain correction calculations done by a µC

4 SHUNT RESISTOR SWITCHING

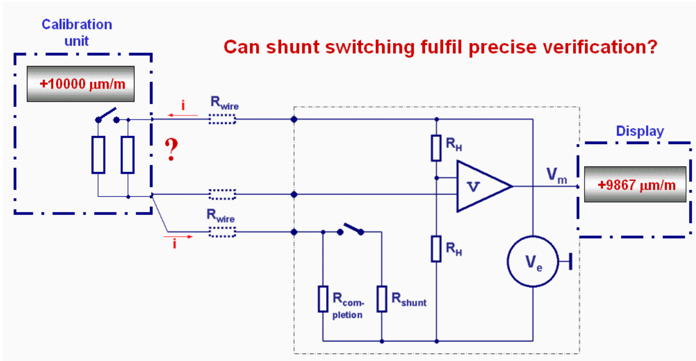

Fig. 6: Shunt switching

If we look at Fig. 6 then it is obvious that the structure of $R_{completion}$ shunted by R_{shunt} inside the measuring instrument looks like the resistor network inside the calibration unit. Therefore the question arises, "can shunt switching be used for precise calibration?". But there are two things more complicated for the shunt switching situation than for the calibration procedure performed by a calibration unit. First, the calibration unit mostly is directly connected to the amplifier input and therefore no errors due to extended cable length occur. Secondly the counterpart of the ¼-bridge calibration unit is the very precise completion resistor $R_{completion}$. In cases of shunt calibration the outer ¼-bridge is a strain gage which may have a big resistance deviation due to tolerances and pre-strain. And of course if the strain gage is connected over a longer distance the resistance of a single wire may exceed 10 Ω. Both factors are supposed to corrupt the accuracy of the shunt calibration.
So let us first have a look on how the shunt signal is influenced by large tolerances of the outer ¼-bridge (resistance change of the strain gage) and secondly let

us see how errors due to voltage drops across the connection wire can be avoided.

5 RELATION BETWEEN CIRCUIT SENSITIVITY AND STRAIN GAGE RESISTANCE TOLERANCE

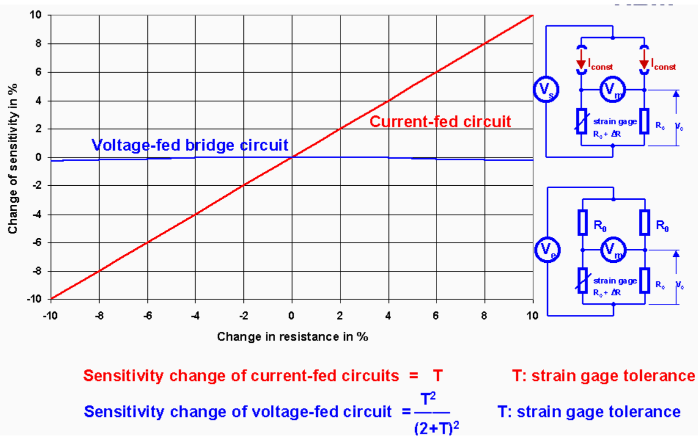

Fig. 7: Sensitivity as a function of strain gage resistance tolerance

The resistance change of a strain gage as a function of strain is directly proportional to the respective total resistance of the strain gage.

With a gage-factor of k = 2 a 120 Ω-strain gage changes by 0.24 mΩ per µm/m and a 350 Ω-strain gage changes by 0.70 mΩ per µm/m. And of course if the strain gage had a 10% higher resistance of 385 Ω it would change by 0.77 mΩ per µm/m. When large strains are applied to a strain gage its resistance may change by many percent and therefore its sensitivity (mΩ per µm/m) will also change accordingly [1].

So if a strain gage is put into a circuit with constant current excitation, we will get a 10% higher output per µm/m if the strain gage resistance is 110% of the nominal value and a 10% lower output if the strain gage resistance is only 90% of the nominal value.

If we put these same strain gages into a voltage fed bridge circuit the sensitivity for strain measurements stays almost constant.

The reason for this behavior is that the non-linearity of the bridge (mV/V = f $_{(\Delta R)}$) compensates the non-linearity of the strain gage behavior (ΔR = f $_{(strain)}$) almost completely.

We can put strain gages with resistance tolerances up to ±6% (equal to pre-strain of ±30000 µm/m) into voltage fed bridge circuits and the sensitivity in mV/V per µm/m changes less than 0.1% (see Fig. 7 and 8).

If sensitivity stays constant no linearity error occurs and vice versa. Therefore bridge circuits measure very linear strain signals and on the other hand show non-linear behavior when measuring large resistance change ΔR. The opposite is true with constant current fed circuits. They measure very linear ΔR but show large linearity errors in case of strain measurements.

Fig. 9 shows the linearity errors for strain signals in the range of ±20000 µm/m. The linearity error of current fed circuits in this case is up to ±2% (400 µm/m of 20000 µm/m) whereas the linearity error of bridge circuits is only ±0.01% (2 µm/m of 20000 µm/m) [1].

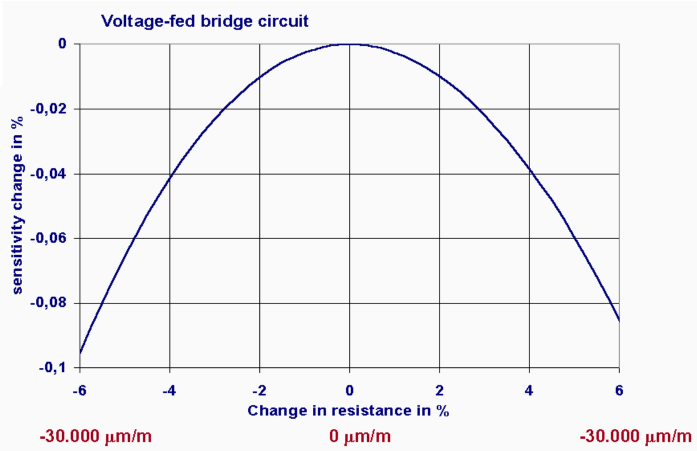

Fig. 8: Bridge sensitivity as a function of SG resistance

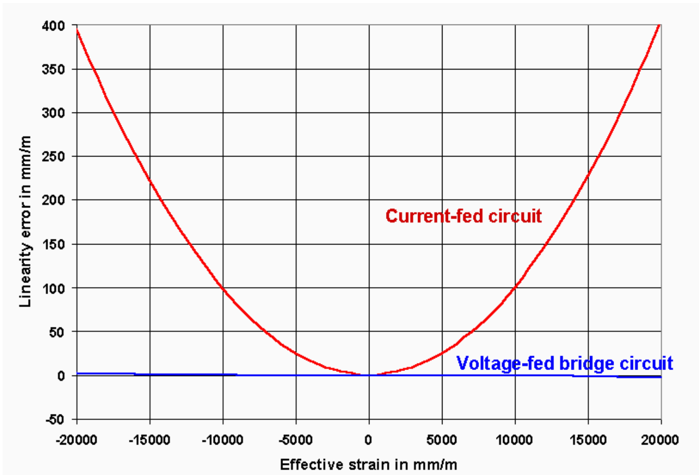

Fig. 9: Linearity errors of constant current and voltage-fed bridge circuits

6 SHUNT SIGNALS STAY ALMOST CONSTANT IN WHEATSTONE BRIDGE CIRCUITS

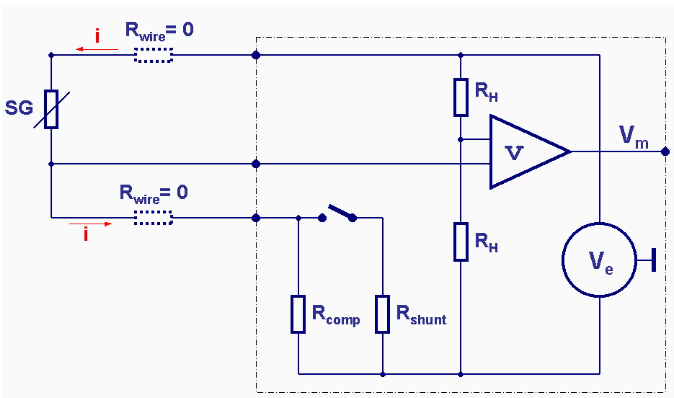

Fig. 10: Very precise shunt signal if wire resistances are zero, also if SG has large tolerances

Now let us go back to the shunt signal topic and look at Fig. 10. If wire resistances are supposed to be zero they cannot cause a sensitivity error. We learned that strain changes the resistance of the strain gage SG proportional to its momentary total resistance.
We get a change as a percentage of the momentary resistance. We learned also that the bridge circuit will measure almost the same electrical signal in mV/V for a definite amount of strain, independent of the strain gage tolerances.
If the shunt resistor R_{shunt} is switched parallel to the completion resistor $R_{completion}$ the resistance change is also a definite percentage of the completion resistor.
If the bridge measuring signal in mV/V is proportional to a percentage change of the strain gage SG then it is also proportional to a percentage change of the completion resistor $R_{completion}$, almost independent of the resistance tolerance of the strain gage resistor SG.
Fig. 11 shows these low dependency. If the nominal strain gage resistance value is 350 Ω and the tolerances were $\pm$10% (315 Ω …. 385 Ω) a shunt signal of 1 mV/V does not change more than approximately $\pm$0.1%.

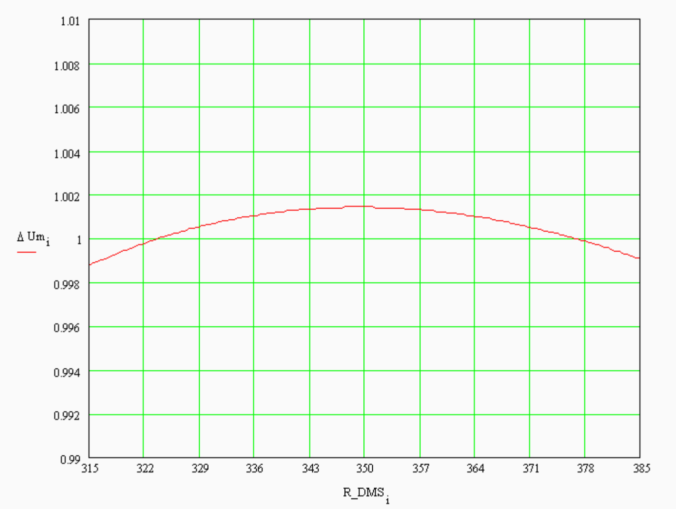

Fig. 11: 1 mV/V shunt signal as a function of strain gage resistance

7 ELIMINATION OF WIRE RESISTANCE IMPACT

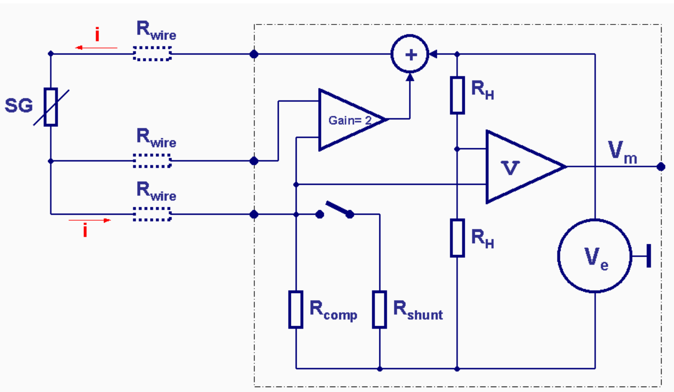

Fig. 12: 3-wire circuit with wire resistance compensation

The next step to go is to eliminate the measuring errors caused by the voltage drops across the connection wires and plug contacts. HBM uses an improved 3-wire-technique as shown in Fig. 12. The voltage drop across one supply wire and plug contact is fed to a special amplifier with a gain of two and its output voltage is added to the excitation voltage. By doing this also the voltage drop of the second supply wire is compensated and the shunt signal behaves as good as if wire resistances were zero.

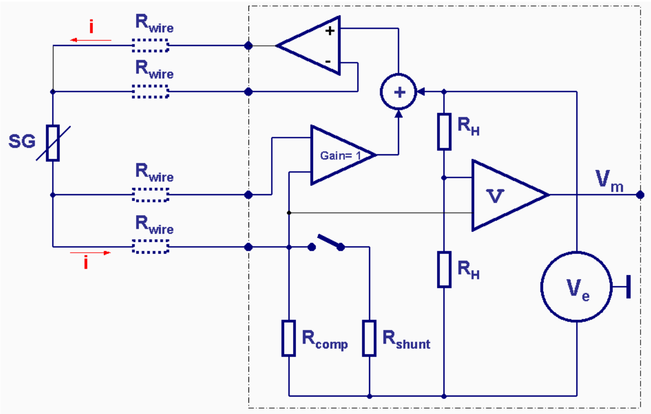

Fig. 13: 4-wire circuit with wire and plug resistance compensation

The standard 3-wire circuit and also the improved HBM-3-wire circuit depends strongly on the symmetry of the wire resistances and on the fact that low plug contact resistance has only small impact.
A better solution therefore is the HBM-4-wire technique shown in Fig. 13. Here the voltage drop across each supply wire and single plug contact is measured and added to the total supply voltage of SG and R_{comp} individually. With this method a perfect wire and contact resistance compensation is possible.

8 MEASURING WITH CONFIDENCE

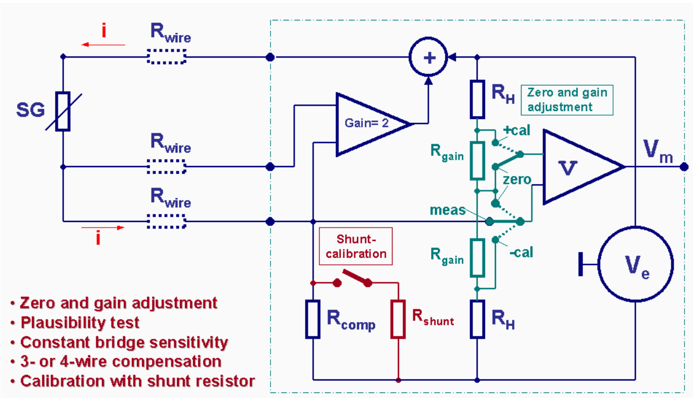

Fig. 14: Structure of a system for high measuring confidence

All ideas explained above are put together in the circuit diagram of Fig. 14. There are five main features of the structure of this circuit.

a) By automatically adjusting zero and gain the errors of the amplifier can be eliminated.

b) The raw-values (input values of the µC in Fig.5) are checked for plausibility. Although these values are only used for calculations and may vary in a wide range their absolute measured values are not allowed to differ for more than $\pm 3\%$ from their theoretical value, otherwise the amplifier sends an error message. The aim is to avoid that the auto calibration procedure repairs too big component drifts which may not be normal and which may cause linearity errors and higher noise voltages.

c) The bridge characteristic of providing a constant sensitivity also if the strain gage resistance differs from its standard value very much is important.

d) With improved HBM 3-wire and 4-wire circuits the impact of voltage drops across the supply wires can be suppressed.

e) And last but not least with this given qualities the whole measuring chain from strain gage to display can be calibrated with shunt resistor switching technique.

9 AMPLIFIER AND SENSOR DIAGNOSIS

With auto calibration of the amplifier and shunt calibration of the complete measuring chain it is possible to install automatic test procedures. Especially in big systems with hundreds or even thousands of measuring channels it is important that we can trust the measuring system and its measurements.

Tab. 1 shows an example of how amplifier and sensor diagnosis can be carried out. The values in the table are really taken measurements from ¼-bridge channels. To prove the shunt calibration theory some 350Ω resistors (in place of strain gages) were connected to the first 8 measuring channels (1-12-1…8) whereas 8 resistors of 329 …371Ω (-6% ….+6%) are measured by the next 8 channels (1-13-1...8). To the channels starting at 1-14-1 nothing is connected (open input).

Description of the columns from left to right:

The first column is the number of the hardware channel. 1-12-6 e.g. means 19"-rack 1, slot 12, measuring channel 6.

The next column ("Channel") can show the individual names of the measuring channel given by the user. In Tab. 1 the default values, equal to column 1 are used. The third column shows the measurements without shunt resistor switching. The upper 8 channels show values lower than ± 800 µm/m, meaning that the tolerances of the connected 350Ω resistors were <0.16%. The next 8 measurements show values from approximately –30000 µm/m, -20000 µm/m, -10000 µm/m, 0 µm/m, 0 µm/m, +10000 µm/m, 20000 µm/m and +30000 µm/m because the connected resistors have got tolerances from –6% to +6%.

The fourth and fifth columns show the auto calibration measured reference points which are to be 0 µm/m and 16000 µm/m.

Amplifier and Sensor Diagnosis

File Tests Actions

	Channel	Reading MEAS	Reading NULL	Reading CAL	Shunt	Nominal Shunt	Wiring OK/NOK	SG Ω Tol.
1-12-1	Channel_01_12_001	-346 µm/m	0 µm/m	15999 µm/m	2016 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-2	Channel_01_12_002	119 µm/m	0 µm/m	16000 µm/m	2015 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-3	Channel_01_12_003	794 µm/m	0 µm/m	16000 µm/m	2014 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-4	Channel_01_12_004	685 µm/m	0 µm/m	16000 µm/m	2014 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-5	Channel_01_12_005	363 µm/m	0 µm/m	16000 µm/m	2015 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-6	Channel_01_12_006	158 µm/m	0 µm/m	16000 µm/m	2016 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-7	Channel_01_12_007	413 µm/m	0 µm/m	16000 µm/m	2016 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-12-8	Channel_01_12_008	297 µm/m	0 µm/m	16000 µm/m	2016 µm/m	2016 µm/m	OK	350 Ω, ~0%
1-13-1	Channel_01_13_001	-31956 µm/m	0 µm/m	16000 µm/m	2016 µm/m	2016 µm/m	OK	329 Ω, -6%
1-13-2	Channel_01_13_002	-20658 µm/m	0 µm/m	16000 µm/m	2015 µm/m	2016 µm/m	OK	336 Ω, -4%
1-13-3	Channel_01_13_003	-10358 µm/m	0 µm/m	16000 µm/m	2015 µm/m	2016 µm/m	OK	343 Ω, -2%
1-13-4	Channel_01_13_004	-387 µm/m	0 µm/m	16000 µm/m	2017 µm/m	2016 µm/m	OK	350 Ω, 0%
1-13-5	Channel_01_13_005	208 µm/m	0 µm/m	16000 µm/m	2014 µm/m	2016 µm/m	OK	350 Ω, 0%
1-13-6	Channel_01_13_006	9974 µm/m	0 µm/m	16000 µm/m	2016 µm/m	2016 µm/m	OK	357 Ω, +2%
1-13-7	Channel_01_13_007	19370 µm/m	0 µm/m	16000 µm/m	2014 µm/m	2016 µm/m	OK	364 Ω, +4%
1-13-8	Channel_01_13_008	29941 µm/m	0 µm/m	16000 µm/m	2015 µm/m	2016 µm/m	OK	371 Ω, +6%
1-14-1	Channel_01_14_001	OVFL	0 µm/m	16000 µm/m	OVFL	2016 µm/m	NOK	NC
1-14-2	Channel_01_14_002	OVFL	1 µm/m	16000 µm/m	OVFL	2016 µm/m	NOK	NC
1-14-3	Channel_01_14_003	OVFL	1 µm/m	15999 µm/m	OVFL	2016 µm/m	NOK	NC
1-14-4	Channel_01_14_004	OVFL	0 µm/m	15999 µm/m	OVFL	2016 µm/m	NOK	NC

Tab 1: Real measurements with amplifier auto calibration and measuring chain shunt calibration

The sixth and seventh columns show the measured shunt difference signal and the expected nominal shunt difference signal. Because the shunt switching generates a signal step of 1.008 mV/V (which was arbitrarily chosen) the nominal strain is 2016 µm/m (k=2). With other k-factors and other strain gage resistances these nominal shunt signals would change, so for ease of use this nominal value column is included. The measured signals are always compared with the nominal values and if more than ±0.2% difference would occur an NOK would be signaled in the eighth column. Both 8-channel groups show "OK" and also the group with 350Ω resistors of ±6% tolerance shows only shunt calibration errors of 0.1% maximum which is mainly caused by the shunt resistor tolerance of 0.1%.

10 TRACEABILITY SITUATION

With auto-calibration and an automatic adjustment mechanism for zero and span, amplifier precision can be made very high and reliable. Such amplifiers may be replaced in case of a break-down by plugging in a new unit without the necessity to repeat a calibration procedure manually.
The shunt calibration is a valuable additional means to carry out an independent check of gain stability across the whole measuring chain (wiring and amplifier).
This gives a high certainty that everything works correct and with the expected precision.
With the shunt calibration procedure only a validation is carried out, no adjustment is made.
During the production process each amplifier is calibrated by a calibration unit (see Fig. 1) which is traced to the National Bureau of Standard (PTB).
The shunt resistors are not adjusted somehow, we always use resistors of 86.6 kΩ/ 0.1% and 30 Ω field effect switches which add up to a total resistance of 86.63 kΩ.
For the commonly used strain gages of 120 Ω, 350 Ω, 700 Ω and 1000 Ω the calculation of the theoretical shunt signals results in 0.346 mV/V (120 Ω), 1.0078 mV/V (350 Ω), 2.012 mV/V (700 Ω) and 2.8690 mV/V (1000 Ω). The PC control program converts these theoretical mV/V-values into the used physical units e.g. µm/m (see. Tab.1) and compares these results with the measurement results coming from the amplifiers.

Actually, there are two independent, differently traced calibration methods applied.
First traced calibration method: Theoretical resistance values have been realized by a National Institute of Standard into a Primary Calibration Standard. An HBM calibration unit (Secondary Standard) is traced to this Primary Calibration Standard. The amplifier units then have been calibrated by this Secondary Standard.
Second traced calibration method: A shunt calibration resistor for a signal of 1.008 mV/V (350 Ω) was calculated as 86.6 kΩ. These resistors are produced by a resistor manufacturer who traces the impedance value also independently to a National Institute of Standard. These resistors then are used as shunt resistors inside our amplifiers and the generated amplitudes are compared with the theoretical calculated amplitudes.

With the first method we trace the sensitivity of the amplifier units via two calibration units (Secondary Standard and Primary Standard) to the real theoretical reference value.
With the second method we trace the shunt calibration signal via a precise resistor which was measured by an instrument from the resistor manufacturer which was also traced to a Primary Standard and then to the equivalent theoretical value.
Both ways are absolutely uncorrelated and that is why with shunt switching a real traced calibration can be carried out.
The above described philosophy of precise shunt calibration applies for ¼ bridges only. In case of half and full bridges precise shunt calibration is only possible if the shunt resistor is connected to the outer bridge via two additional wires and also only if the impedance of the outer bridge is well known.
But in big measuring systems in the field of Experimental Stress Analysis ¼ bridges are the absolute majority. And therefore this new method of shunt calibration relieves from a lot of tedious calibration tasks and provides a very high certainty for the correctness of the measurements.

11 REFERENCES

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www.hbm.com
(Applications/ Publications / Technical Articles)